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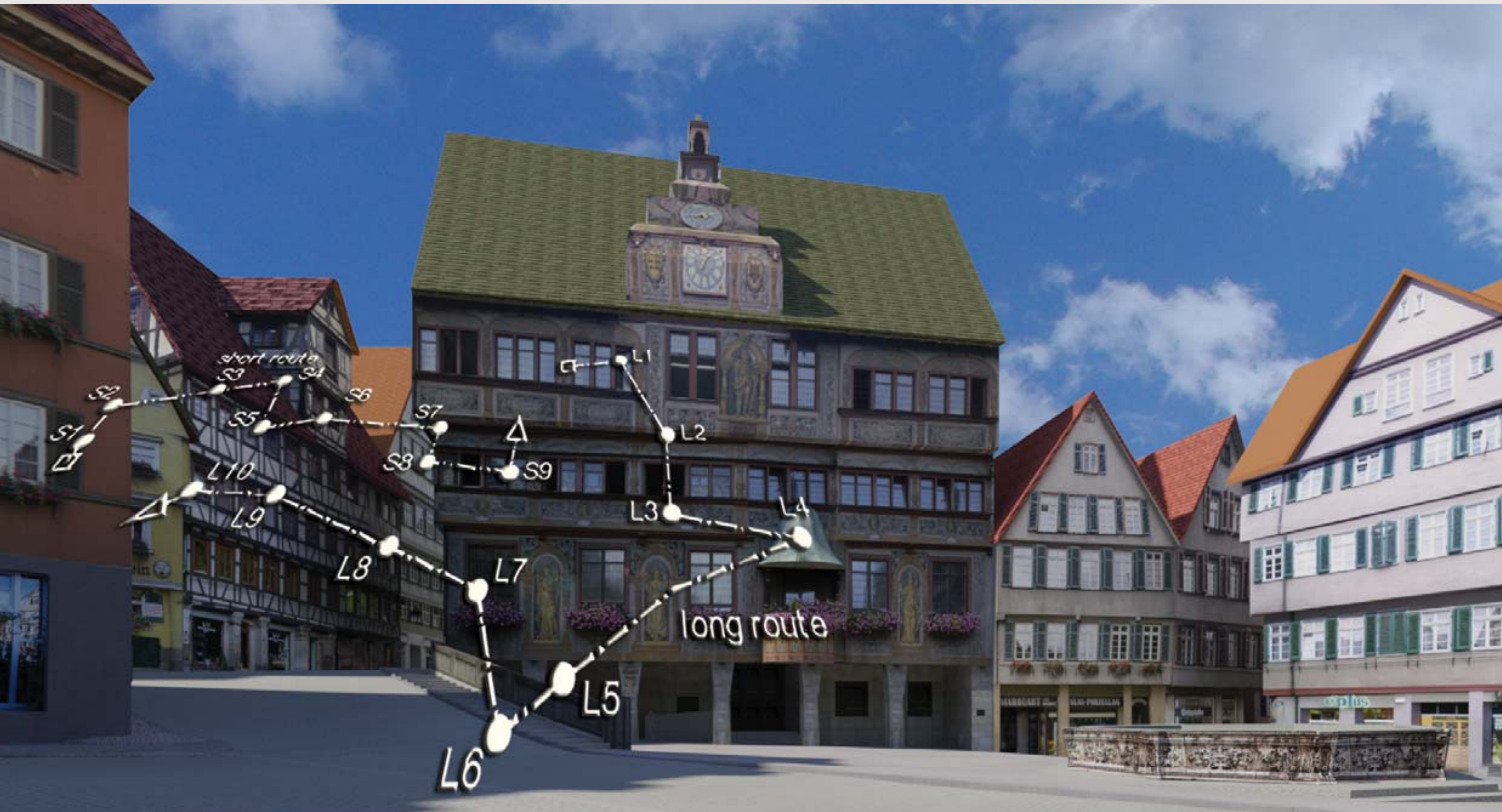
Strategies of Orientation in Environmental Spaces



Strategies of Orientation in Environmental Spaces

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Abstract

Orientation in space is fundamental for all humans and most other animals. Accomplishing goals often requires moving through environmental spaces such as forests, houses, or cities. Several mechanisms were evolved in order to solve these orientation problems, including spatial updating, route navigation, and reorientation by landmarks and geometry. Human orientation capabilities build upon these and other fundamental mechanisms. Compared to non-human animals, humans demonstrate a greater flexibility during orientation tasks. They are able to apply various strategies to fulfil one orientation goal, such as navigating to a known location. In this work, we examined which orientation strategies human navigators apply and how efficient these strategies are. We focused on memory strategies for encoding spatial knowledge and on planning strategies especially during wayfinding.

In Study 1, we examined memory strategies used to encode a route. Participants learned two routes in a novel photorealistic virtual environment displayed on a 220° screen, while they were disrupted by either a visual, a spatial, a verbal or - in the case of the control group - no secondary task. In a subsequent wayfinding phase, the participants were required to navigate the routes again. The interferences between verbal and spatial secondary task and the encoding of wayfinding knowledge were greater than that between the visual secondary task and the encoding of wayfinding knowledge. This suggests that participants rely on a verbal and spatial memory strategy. In Study 2 and Study 3, we tried to determine more precisely the kind of space involved in this spatial strategy: either a map-like space (called figural space), or the visible area in the surrounding environment (called vista space).

In Study 2, we tested the hypothesis that the spatial memory strategy relies on a map-like space. If navigators use a map-encoding strategy, specific transformation costs should occur for tasks performed in route perspective (e.g., wayfinding), but not for tasks performed in the same bird's-eye view as the encoded map (e.g., map drawing). To test these predictions, participants learned two routes. In one condition, the route was learned from maps, in the control condition, participants learned the route only from verbal instructions constructed from these maps. Both groups then tried to find these routes and performed route knowledge, direction, and distance estimation tasks from varying perspectives. When tested in the bird's-eye perspective of the maps, the groups differed. Participants, therefore, *did* remember knowledge from the maps. However, for tests in route perspective, especially wayfinding, no differences could be observed. This was also confirmed

in a power analysis. As with Study 1, the results suggest that participants use a verbal strategy for wayfinding. This was supported by participants' subjective reports, as well as by their superior performance in giving directions compared to drawing route maps. These results speak against a strong involvement of figural space in human spatial memory strategy.

In Study 3, we examined whether the spatial memory strategy of wayfinders relies on the geometry of vista spaces. Data from Study 1 was analysed in order to compare performance of all participants at different intersections. We formalised the geometry of an intersection, applying a new direction-specific isovist analysis. Such an isovist analysis computes parameters from the view-shed polygon of the visible area. Using these parameters, we could cluster the intersections into two geometrically dissimilar groups, i.e., t-intersections and non-t-intersections. Participants exhibited better wayfinding performance at non-t-intersections as well as more thorough landmark and route knowledge. Therefore, it seems plausible that the geometric layout of vista spaces plays a role in wayfinding and that the memory strategy navigators use for spatial orientation relies at least partly on the geometry of the vista space. Additional results from Study 3 showed that participants seemed to apply a when-in-doubt-follow-your-nose strategy. They encoded primarily intersections which required a turn; they did not recall well intersections they walked straight through. Better route knowledge and wayfinding performance were traded for a decreased ability to recognise "straight-on" intersections. The when-in-doubt-follow-your-nose strategy shows how planning can interact with memory.

Study 4 and Study 5 were concerned with planning strategies more directly. In Study 4, we examined wayfinding strategies as a function of familiarity. Participants who were familiar and unfamiliar with a complex multi-level building performed six wayfinding and several survey knowledge tasks. We measured strategy by route choice and by "thinking aloud" protocols. Familiar participants preferred a regional planning strategy that involved first heading to the floor on which the goal was located. Overall, this strategy was tied to better wayfinding performance compared to a least angle strategy or a strategy of relying on well-known parts of the building. The regional planning strategy can reduce memory workload during planning and navigation while still providing rather short routes. Route knowledge showed a greater impact on wayfinding performance compared to metric survey knowledge. This was also indicated in Study 1 and Study 2 and varied actively in Study 5.

In Study 5, we examined metric and non-metric strategies. First-time visitors to a complex building solved two wayfinding and two self-localisation tasks. They either used a standard map, which depicted metric relations correctly, or they used a highly schematic map only depicting route information, i.e., the topology (which decision point is connected to which other decision point) and turning information at decision points (straight on, left or right). No differences were found for self-localisation, indicating that all participants focused more on route information. Participants with a schematic map were even better at wayfinding. Metric information, therefore, did not seem to contribute much to wayfinding and self-localisation.

As indicated in the studies, human strategic choice can often be described with a cost-efficiency criterion. A spatial memory strategy relying on vista spaces requires less transformation costs than a spatial strategy relying on figural spaces. The when-in-doubt-follow-your-nose strategy requires fewer decision points to be encoded in memory, without the risk of getting lost. The efficient regional wayfinding strategy also reduces memory workload during planning and navigation, while still providing rather short routes. Although they facilitate more precise navigation, metric strategies require higher memory and/or computational loads, leading to worse performance overall.

Based on our results we formulated a theoretical framework for orientation in environmental spaces. The strong involvement of a verbal memory strategy in Study 1 and Study 2 led to the dual coding theory of spatial orientation. This theory assumes that human navigators encode environments not only in a visual or spatial format (as probably also non-human animals do), but also in a *verbal* format. This theory can explain biases in spatial memory, help interpret results from wayfinding and reorientation, and provide a basis for more elaborate strategies. The characteristics of mere spatial memory and planning strategies are described in the network of reference frames theory. This theory assumes that spatial memory for environmental spaces consists of a network of vista space reference frames. It proposes a common memory structure for wayfinding and reorientation, provides a common framework for route and survey navigation, and highlights similarities and differences between human and non-human navigators. It can explain results from various areas of spatial orientation, such as orientation specificity, changes due to familiarity, and asymmetries in spatial memory. It also provides ideas for future research including testable predictions. The results of this thesis, as well as the proposed theoretical framework, are meant to be a step forwards in approaching a functional theory of orientation in space.

Zusammenfassung

Die Fähigkeit sich im Raum zu orientieren ist für Menschen und andere Tiere essenziell wichtig. Um Ziele zu erreichen ist es oft notwendig, sich durch Navigationsräume („environmental spaces"), wie z.B. Wälder, Gebäude oder Städte, zu bewegen. Zur Lösung solcher Orientierungsaufgaben evolvierten verschiedene Orientierungsmechanismen, z.B. Pfadintegration, Routennavigation oder die Reorientierung an Landmarken bzw. der Umgebungsgeometrie. Menschliche Orientierungsfähigkeiten bauen auf diesen Mechanismen auf. Dabei legen Menschen eine viel größere Flexibilität an den Tag als andere Tiere. So sind Menschen in der Lage, unterschiedliche Strategien zu verwenden, um ein und dasselbe Ziel zu erreichen.

Die vorliegende Arbeit untersucht, welche Strategien Menschen zur Orientierung im Raum einsetzten und wie erfolgreich diese Strategien sind. Dabei liegt der Fokus auf Gedächtnisstrategien zur Enkodierung räumlichen Wissens sowie auf Planungsstrategien, vor allem beim Wegfinden.

Studie 1 untersuchte Strategien zur Enkodierung von Wegen. Die Versuchspersonen beobachteten ein Video, dass zwei Wege durch eine photorealistische virtuelle Stadt darstellte, die auf eine 220° große Leinwand projiziert wurden. Während sie sich die Wege einprägten, bearbeiteten die Versuchspersonen verschiedene Nebenaufgaben - entweder eine visuelle, eine räumliche, eine verbale - oder keine Nebenaufgabe. In der anschließenden Wegfindungsphase sollten die Versuchspersonen die gelernten Wege mit Hilfe eines Joysticks ablaufen. Zu beobachten war, dass die verbale und die räumliche Nebenaufgabe stärker mit der Enkodierung von Wissen über Wege interferierten, als die visuelle Nebenaufgabe. Dieses Ergebnis deutet darauf hin, dass man zur Wegfindung eine verbale und eine räumliche Gedächtnisstrategie einsetzt.

Ziel der Studien 2 und 3 war es, genauer zu bestimmen auf welche Art von Raum sich die Gedächtnisstrategie bezieht: den kartenähnlichen Objektraum ("figural space") oder den sichtbaren Raum, der die Menschen unmittelbar umgibt ("vista space")?

Studie 2 überprüfte die Hypothese, dass die räumliche Gedächtnisstrategien sich auf kartenähnliche Räume ("figural spaces") beziehen. Dieser Hypothese folgend ist zu erwarten, dass das Enkodieren einer Karte bestimmte Transformationskosten nach sich zieht, wenn dieses Wissen aus einer Routenperspektive, z.B. beim Wegfinden, abgerufen wird. Solche Transformationskosten sollten jedoch nicht bei Aufgaben auftreten, die in der Vogelperspektive bearbeitet werden, wie z.B. das

Zeichnen einer Karte. Die Versuchspersonen lernten zwei Wege, entweder anhand von Karten oder - als Kontrollbedingung - anhand von Wegbeschreibungen, die auf Basis dieser Karten generiert wurden. Anschließend sollten beide Gruppen die Wege laufen sowie Aufgaben zum Routenwissen und zur Schätzung von Richtungen und Entfernungen aus unterschiedlichen Perspektiven bearbeiten. Fand die Aufgabe aus der Vogelperspektive heraus statt, so unterschieden sich die Gruppen voneinander. Die Versuchspersonen hatten also etwas von den Karten gelernt. Fand die Aufgabe allerdings aus der Routenperspektive heraus statt, so ergaben sich, z.B. in der Wegfindungsaufgabe, keine Unterschiede. Dieser Nulleffekt wurde auch durch eine Analyse der Teststärke unterstützt. Wie in Studie 1 legt das Ergebnis nahe, dass die Versuchspersonen eine verbale Gedächtnisstrategie zum Enkodieren von Wegen einsetzen. Diese Interpretation wird zudem durch Befragungsdaten gestützt sowie durch die bessere Leistung der Versuchspersonen bei der Beschreibung als beim Aufzeichnen der Wege. Insgesamt deuten die Ergebnisse *nicht* auf eine starke Beteiligung von kartenähnlichen Räumen („figural spaces") beim räumlichen Enkodieren von Wegen hin.

Studie 3 untersuchte, ob die räumliche Gedächtnisstrategie auf der Geometrie der sichtbaren Umgebung („vista spaces") beruht. Dazu wurden die in Studie 1 generierten Daten so ausgewertet, dass die Leistung aller Versuchspersonen an unterschiedlichen Kreuzungen miteinander verglichen werden konnten. Wir parametrisierten die Kreuzungsgeometrie mit Hilfe einer neuen, richtungsabhängigen Isovist-Analyse, die das eingeschränkte menschliche Sichtfeld berücksichtigt. Eine Isovist-Analyse berechnet unterschiedliche Parameter anhand des Polygons, das der sichtbaren Bodenfläche entspricht. Aufgrund dieser Parameter konnten wir die Kreuzungen in zwei, einander geometrisch möglichst unähnliche, Gruppen einteilen: T-Kreuzungen und nicht-T-Kreuzungen. In Wegfindungsaufgaben sowie in Aufgaben zum Landmarken- und Routenwissen zeigten die Versuchspersonen an nicht-T-Kreuzungen bessere Leistungen. Es erscheint daher plausibel anzunehmen, dass die Geometrie des sichtbaren Umgebungsraumes in der Wegfindung eine Rolle spielt. Ebenso scheint die räumliche Gedächtnisstrategie, wenigstens zum Teil, auf einem solchen Raum aufgebaut zu sein. Weitere Ergebnisse aus Studie 3 zeigen, dass die Versuchspersonen eine „im-Zweifel-geradeaus" Strategie verwenden. Sie erkennen zwar vor allem Kreuzungen wieder, an denen sie abbiegen müssen, allerdings zeigen sie bessere Leistungen sowohl beim Wegfinden als auch bei Aufgaben zum Routenwissen, wenn sie an einer Kreuzung geradeaus laufen mussten. Solch eine Strategie ist ein schönes Beispiel für die Verschränkung von Gedächtnis- und Planungsstrategien.

Die Studien 4 und 5 beschäftigten sich konkreter mit Planungsstrategien. Studie 4 untersuchte Wegfindungsstrategien und deren Veränderung aufgrund von Erfahrung. Versuchspersonen, die mit einem komplexen mehrstöckigen Gebäude vertraut waren, wurden in sechs Wegfindungs- und verschiedenen Überblicksaufgaben mit Versuchspersonen verglichen, denen dasselbe Gebäude nur wenig vertraut war. Die Erhebung der eingesetzten Strategien erfolgte anhand der Wegentscheidungen sowie anhand von Protokollen des lauten Denkens. Versuchspersonen, die mit dem Gebäude vertraut waren, bevorzugten eine regionale Planungsstrategie, in dem sie immer versuchten, zuerst in das richtige Stockwerk zu laufen. Diese Strategie war eher mit guter Wegfindungsleistung verknüpft, als eine Überblicksstrategie oder eine Strategie, die darauf basiert einen Weg zu wählen der - so weit wie möglich - durch gut bekannte Gebäudeteile führt. Die regionale Planungsstrategie reduziert die notwendigerweise gespeicherten Entscheidungspunkte und führt trotzdem zu eher kurzen Wegen. Insgesamt hatte Routenwissen einen größeren Einfluss auf die Wegfindungsleistung als Überblickswissen. Dies zeigte sich auch in den Studien 1 und 2 wurde in Studie 5 aktiv variiert.

Studie 5 untersuchte metrische und nicht-metrische Strategien. In einem ihnen unbekannten Gebäude lösten Versuchspersonen zwei Wegfindungs- und zwei Selbst-Lokalisationsaufgaben. Dazu verwendeten sie entweder eine Standardkarte mit korrekten metrischen Relationen oder eine stark schematisierte „Routenwissen-Karte“, die nur die Topologie (welche Entscheidungspunkte sind mit welchen verbunden) und die Abbiegeinformation an Entscheidungspunkten (rechts, links, geradeaus) richtig darstellte. In der Selbst-Lokalisationsaufgabe konnten keine Unterschiede zwischen den Gruppen gefunden werden. Dies deutet darauf hin, dass alle Versuchspersonen sich eher an der, in beiden Karten korrekt dargestellten, Routeninformation orientierten. In der Wegfindungsaufgabe zeigte die Gruppe mit der schematisierten Karte sogar bessere Leistung. Dieses Ergebnis lässt vermuten, dass metrische Informationen nicht wesentlich zur Wegfindung und Selbst-Lokalisation beitragen.

Insgesamt können die Studien so interpretiert werden, dass menschliche Strategiewahl oft einem Kosteneffizienzkriterium folgt. Eine räumliche Gedächtnisstrategie, die auf die sichtbaren Umgebungsräume („vista spaces“) zurückgreift, führt zu geringeren Transformationskosten als eine räumliche Strategie, die auf karten-ähnlichen Räume („figural spaces“) basiert. Mit einer „im-Zweifel-geradeaus“ Strategie müssen weniger Entscheidungspunkte enkodiert werden, ohne Gefahr zu laufen, sich hinterher zu verlaufen. Die effiziente regionale Planungsstrategie benötigt weniger Gedächtniskapazität sowohl während der Planung als auch während des Laufens der Wege und liefert trotzdem eher kurze Wege. Metrische Strategien ermöglichen zwar präzisere Navigation, stellen aber höhere Anforderungen an das Gedächtnis, bzw. die Verarbeitung. Daher können sie schlechtere Leistungen zur Folge haben.

Die beobachteten Ergebnisse führten zur Formulierung einiger theoretischer Positionen bezüglich der Orientierung in Navigationsräumen (“environmental spaces”). Die starke Beteiligung der verbalen Gedächtnisstrategie in Studie 1 und 2 resultierte in der „Zweifachkodierungstheorie der Raumorientierung". Laut dieser Theorie enkodieren Menschen bei Orientierungsaufgaben ihre Umwelt nicht nur in einem visuellen oder räumlichen Format, wie das andere Tiere vermutlich auch tun, sondern verwenden zudem ein verbales Format. Die Zweifachkodierungstheorie erklärt systematische Verzerrungen im Raumgedächtnis, sie hilft bei der Interpretation von Ergebnissen aus der Forschung zur Wegfindung und Reorientierung und sie stellt eine Basis für elaboriertere Strategien bereit. Die rein räumlichen Aspekte von Gedächtnis- und Planungsstrategien sind in der hier formulierten „Referenzrahmennetztheorie" beschrieben. Diese noch spekulative Theorie nimmt an, dass das Raumgedächtnis für Navigationsräume aus einem Netzwerk einzelner Referenzrahmen besteht, die sich jeweils auf einen sichtbaren Umgebungsraum beziehen. Im Gegensatz zu anderen Theorien schlägt die „Referenzrahmennetztheorie" eine einheitliche Gedächtnisstruktur für Wegfindung und Reorientierung sowie für Routen- und Überblickswissen vor. Zudem zeigt sie Gemeinsamkeiten und Unterschiede zwischen menschlicher und nicht-menschlicher Raumorientierung auf. Sie erklärt unterschiedliche Ergebnisse, unter anderem zur Orientierungsspezifität, dem Einfluss von Erfahrung und der Asymmetrie des Raumgedächtnisses. Weiterhin wirft sie Fragen für zukünftige Experimente auf und macht dabei verschiedene empirisch überprüfbare Vorhersagen. Die hier vorgestellten empirischen Ergebnisse sowie der in dieser Arbeit vorgeschlagene theoretische Rahmen stellen einen Betrag dar, zur Entwicklung einer funktionellen Theorie der Orientierung im Raum.

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Notes on the printed version

More recent versions of the studies presented in this thesis are published or in press in the following:

Study 1 is now published in Cognitive Science, 32, 755-770.

Study 2 is currently “in press” in the Journal of Spatial Science.

Study 3 is currently “in press” in Environment and Planning B.

Study 5 is now published in T. Barkowsky, M. Knauff, G. Ligozat & D.R. Montello (Eds.) Spatial Cognition V (pp. 381–400). Berlin: Springer.

für Cordula

Contents

1 Introduction

Orientation in space is fundamental for all humans and other animals. Accomplishing our goals most often requires moving through complex spaces such as houses or cities also called environmental spaces. We move from our home to work, to our office, to the supermarket or to the new pub. For well known routes this is basically effortless. We do not even notice the tremendous performance we accomplish every day. This changes when we are no longer able to use the memory of our environment, e.g., Alzheimer patients sometimes are unable to find even their way back home (e.g., Monacelli, Cushman, Kavcic & Duffy, 2003). In robotics it is considered a difficult problem to build robots that are able to navigate through the world and at the same time keep track of where they are (e.g. Stachniss, 2006). We realize what orientation problems can occur when trying to reach a completely unknown location. For new locations we cannot rely on our memory and just follow learned routes, but we have to rely on external sources of information which tell us where our goal is located and how we can get there. Some of these external sources are gestures, verbal wayfinding directions, signs and maps.

Navigating to unknown locations is not a specific human capability. Some migratory birds genetically “know” in which direction to fly to when winter is approaching (e.g., Berthold, Helbig, Mohr & Querner, 1992). Other species are able to communicate locations in order to reach unknown locations: Ants follow olfactory trails laid out by their conspecifics (Hölldobler, 1971) and bees learn the angle and distance of a food source by observing another bee’s dance (e.g., von Frisch, 1967). However, none of these communications of spatial locations is as flexible as humans use of verbal directions or maps.

The examples mentioned show that several biological and technical solutions are possible to one specific orientation problem. The present work is bound to understand the information processing underlying orientation in such a broad perspective seen from different point of views such as psychology, biology or computer science. The most relevant questions are “What strategies enable to achieve goals, e.g., to know where one is or to find a specific location in the environment?” and “How is the environment represented?” Our approach to answer these questions follows several implicit assumptions:

In the last decades, in the field of psychology, as well as in artificial intelligence and cognitive science, explanations for various problems changed from assuming one general representation format together with one general problem solving mechanism towards domain-specific knowledge and multiple, problem specific forms of representations as well as mechanisms operating on them (e.g., Tye, 1991; Sloman, 1984; Strube, 1996). This change brought these fields closer to biology where multiple mechanisms guiding behaviour were assumed more often (e.g., McFarland, 1999). The present work will follow this development in theory. It will focus on multiple forms of representations as well as multiple mechanisms used for orientation.[1]

A second assumption of this work is a rather continuous phylogenetic and ontogenetic development. Orientation mechanisms can evolve along with new sensory inputs (e.g. Wehner, 1994) or strategies develop with higher cognitive capacities in children (e.g., Cornell, Heth & Alberts, 1994). Other mechanisms such as human path integration might not be used so intensively any more (cf., Loomis et al., 1993). New abilities, suc as language, enable new strategies for orientation problems, e.g., giving verbal directions to somebody. Such new strategies, however, are not assumed to replace *all* other existing mechanisms. It is rather unlikely that humans orient completely differently than non-human animals or that human adults orient completely differently than children. Taking this perspective of a rather continuous development implies also that we can learn about orientation mechanisms in adults by looking at how children and non-human animals orient.

This research is within the area of cognitive psychology. It is not in developmental, biological and personality psychology, nor in biology, cognitive science, neuroscience or artificial intelligence. It is strictly empirical and behavioural. This reseach does not imply any formal modelling of experimental data. However, this work tries to take into account findings from all the mentioned research areas. Psychology in general and cognitive psychology in particular is in touch with all the mentioned disciplines (Prinz & Müsseler, 2002). Results from these disciplines are bound to place constraints and suggestions on possible theories used to explain adult orientation in space. In that sense the present work will consider findings from various sources. However, it is far beyond the scope of this work to discuss all related areas, even in such a relatively young interdisciplinary field such as spatial cognition. Due to the empirical and behavioural orientation of this work, it will mainly consider behavioural results from orientation in animals as well as developmental, biological and personality psychology. However, when highly relevant, findings from neuroscience, cognitive science and artificial intelligence will also be discussed.

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[1] Due to Occam's razor, explanations requiring fewer theoretic assumptions are preferable to explanations requiring more assumptions. This is not necessarily an argument against multiple representations or mechanisms. Explaining empirical results with one general representation format - usually propositional/symbolic - can require more *additional* assumptions than explaining them with multiple representations.

We will, first, review the literature concerning orientation in environmental spaces, second, we will present and discuss the results of five studies regarding open problems in strategies of orientation and third, we will discuss these results in the broad perspective of spatial orientation research.

2 Theory

In order to discuss orientation in environmental spaces, one has to know, what orientation and what an environmental space is. Therefore, the first section will define the terms ‘space’ and ‘orientation’. Spatial orientation is about achieving goals, e.g., to locate our current position or reach a certain location. In section two we will look at these goals. To reach these goals we apply different orientation mechanisms e.g., the strategy of trying to minimise the deviation from the direction of the goal location during locomotion. Section three will regard these mechanisms. In order to apply a strategy or another mechanisms for orientation knowledge is required, e.g., the location of the goal relative to our current position. In section four we will discuss types and organisation of spatial knowledge. We obtain this knowledge either directly by experiencing our environment or we obtain it indirectly from other sources, such as maps or verbal directions. We not only obtain the knowledge from different sources we also use different memory systems to represent it, e.g. visual, spatial or verbal memory. In section five we will look the representational format of this knowledge.

2.1 Orientation, spaces, and maps

This thesis is about orientation in environmental spaces. By orientation in space we mean orientation in a *physical space*, not orientation in life or in metaphorical spaces such as mathematical space or the ‘hyperspace’ of the internet. We also do not consider all possible physical spaces to orient within, but limit ourselves to spaces which surround us and which we apprehend by locomotion. Montello (1993) distinguishes these *environmental spaces* from geographical spaces which are too big to apprehend by locomotion and therefore have to be learned via maps. In geographical spaces one could tell whether Napoli or New York is further to the north or whether Reno or San Diego is further to the west (cf. Stevens & Coupe, 1978). In environmental spaces one could walk to a location. Maps also occupy a space. Montello (1993) calls this *figural space.* It is projectively smaller than the body and no locomotion is needed to perceive its properties. He subdivides figural space into pictorial and object spaces, the former referring to small flat spaces such as maps and pictures and the latter to small 3-D spaces such as small objects or distant landmarks. Pictorial spaces can be used to depict environmental or geographical spaces. The last space in this distinction is called *vista space*. It is as large or larger then the body, but can visually be apprehended from a single place without locomotion. It is the space of single rooms, town squares, small valleys and horizons.[2] This work will consider orientation in environmental spaces. In order to do so several vista spaces have to be crossed and participants often refer to the figural space or more specific to the pictorial space of a map. Spaces which are exclusively learned by maps, such as very large geographic spaces, will not be considered. However, as far as maps display environmental spaces they are relevant for this work.

Graphic representations such as maps imply abstraction from the environment, however, since maps often distil and highlight important information, scale is sometimes only roughly preserved (Tversky, 2000). Therefore, for our purposes we can define maps as "two-dimensional graphic representations of spatial relations in an environment". This includes, e.g., a cross section of a building or a route drawn in the sand. It excludes pictures and three-dimensional models.

We defined what spaces we examine, but what exactly do we mean by orientation? Orientation involves goal-directed interaction with an environment (cf. Montello, 2005). These goals can comprise reaching a known location, finding an unknown location, re-orienting oneself after getting lost, or exploring the environment. Orientation involves cognitive aspects such as planning, recognising landmarks, or updating the location of an object during movement. Orientation also involves the execution of behaviour, e.g., motor control for locomotion (cf. Passini, 1992). We will, however, focus on the cognitive rather than the motor aspects of orientation.[3] Definitions for the individual cognitive aspects such as "strategies" or "representations" will be given in the respective sections. Following the mentioned definitions we will examine different strategies in the goal directed interaction with environmental spaces. The next section will discuss the various types of goals in this goal directed interaction.

2.2 Goals

Several goals can be pursued in an environmental space. We will distinguish wayfinding, reorientation, and exploration.

Wayfinding occurs every day when we want to get somewhere: from our bed to the bathroom, from our flat to our work, or from the train station to a conference centre. When finding our way we know where we are and where we want to go. We, e.g., visited our goal location before and, therefore, know it, i.e., we rely on

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[2] Many authors use the distinction between small scale and large scale spaces (e.g. Fields & Shelton, 2006). As this distinction is not defined very well we will not use it here. Both figural and a vista space can be considered as small scale spaces and both vista and environmental spaces can be considered as large scale spaces. For a distinction of spaces similar to Montello (1993) see Tversky (2005).

[3] As this work does not focus on motor control, we do not further subdivide vista spaces, e.g., into action space, i.e., the space within one performs motor actions (cf. Cutting & Vishton, 1995).

our memory of the environment in order to get there. If we have not been to the goal location before, we cannot rely on the internal representation of our memory, but must use an external representation, e.g., a map, verbal direction, or gestures which tell us where the goal is to be found. If we do not know the location of the goal and no external representations are available, we must *search* for the goal. For orientation in daily life such an uninformed search is rather uncommon. Usually we know at least something about a goal location and do not search, e.g., a whole town. Due to the higher relevance in daily life and for this work, we will focus on wayfinding where information about the goal location is available.

Wayfinding, by definition, also involves a selection in which direction to go in an environmental space. A conference centre could, e.g., also be reached by hiring a taxi and telling the driver where to go. This does not involve selecting a direction, as the driver is doing this for us. Wayfinding is delegated to the driver. The same argumentation holds true for taking the train or the plane. In these cases the problem of reaching a goal is solved by planning processes which do not necessarily involve the representation of space.

We consider wayfinding as involving situations in which we know where our goal is to be found and which involves interaction with space in a sense that we decide ourselves where to go based on this knowledge.

Asking where something is in an environment and how it can be reached it is one question, another question is asking where one is in the environment (cf. Allen, 2004). The corresponding goal is to localise oneself when not knowing where one is. We will call this task of finding ones position in an environment *reorientation*, but it is also referred to as self-localisation. For convenience, the term position will be used to refer to the combination of a particular location and a particular heading in space (cf. Rump & McNamara, in press). Reorientation is only necessary when one is disoriented with respect to the environment. Contrary to that, we defined being oriented as a prerequisite for wayfinding, i.e., wayfinding implies that navigators know where are and where the goal is. Sometimes they get lost during wayfinding. Due to our definitions navigators first have to reorient before being able to pursue their goal again.

The last goal we want to describe is simply to learn something about a new environment. For this purpose we look at a map or walk around, e.g, during window-shopping in a new town. Traditionally, this behaviour is called *exploration* (at least for walking around). The explorer is oriented with respect to the environment as in wayfinding and search, but contrary to wayfinding and search no specific location is sought-after. Exploration is an important goal when orienting in space. This work, however, will focus on wayfinding and reorientation.

2.3 Orientation mechanisms

The goals to know where one is (reorientation) and how one can get from here to a certain location (wayfinding) are very common in humans and the rest of the animal kingdom. As achieving these goals is crucial for surviving in many species, various mechanisms have evolved to solve these problems over the past millions of years. These mechanisms can be classified in several ways (e.g., Franz & Mallot, 2000; Gillner & Mallot, 1998; Mallot 1999; Trullier, Wiener, Berthoz & Meyer, 1997; Wang & Spelke, 2002). One very basic distinction is between processes which can be observerd in humans and other animals and strategies which are specific to humans.

2.3.1 Orientation processes

2.3.1.1 Classifications of orientation processes

Several authors have provided classifications of orientation processes. We will look at the approaches provided by Wang and Spelke and by the groups of Trullier and Mallot.

Wang and Spelke. Wang and Spelke (2002) distinguish three processes relevant for orientation: path integration, viewpoint-dependant place recognition and reorientation. Path integration is a process by which the relation of a human or a non-human animal to one or more significant places in the environment is updated continuously during movement. The viewpoint-dependant place recognition operates by template matching of viewpoint-dependent representations of landmarks. It allows navigating from one location to another. The reorientation system looks for congruences between representations of the shape of the surface layout. It focuses on the geometry of the surrounding surface layout as a cue for orientation after being disorientated.

Wang and Spelke regard encapsulated representations of the environment as building blocks for these three proposed mechanisms in animals and humans. Specifically human symbolic capacities enable to construct new spatial representations and strategies to overcome the limits of the more primitive navigational systems.

Trullier and colleagues. Trullier and colleagues (1997) propose several processes based on a review of biologically inspired computational models of navigation in animals: guidance (move in relation to perceptions), place recognition-triggered response (orient relative to specific places), topological navigation (move along known paths) and metric navigation (move in relation to an "overview" of the whole environment /move new paths). As a prerequisite for all other processes a navigator has to be able to approach a location. This could be achieved e.g. by aligning the body with the direction towards the goal and then moving forward. For visual stimuli this is also called beaconing. In *guidance* a navigator acts immediately on the sensor input and a stored sensory input, e.g. follows a wall, or tries to minimise the discrepancy of the current view to a stored view e.g. at the goal. With this mechanism, e.g., a specific location in between several landmarks can be reached in a vista space. In *place recognition-triggered response* a navigator recognises a place visited before and selects a direction to move on so as to reach its current goal. The goal is not visible from the current location so it is a process for reaching goals in environmental spaces. A place in this sense is a set of continuous locations where a navigator selects the same action. The situation is perceived as identical or very similar to a learned one. With place recognition-triggered response a navigator is able to reach a goal, but has no internal representation of the relations between the current place and other places. No planning is involved, i.e. it is not possible to represent the complete route from the current place to the goal. With this process only, a barrier on the route would make it impossible to reach the goal. In *topological navigation* no place-goal-action associations are stored, but place-action-place associations are built and stored in memory. A navigator knows how to get from one remembered place to another and vice verse. This can be thought of as a graph where the nodes represent places and the edges represent actions to reach from one place to another. With a representation like this, planning is possible, i.e. searching for a sequence of places to visit in order to reach the goal. If the selected route was blocked, an alternative route could be planned if contained in the representation. Getting a sequence from the current position to the goal must not be a symbolic search algorithm, but can be achieved by activation spread from the node representing the current position and/or from the node representing the goal. A mechanism selecting the sequence of nodes with the highest activation would give similar results. Such a mechanism would always select the route with the fewest number of nodes. It can, therefore, explain identical behaviour without assuming symbolic planning processes. Contrary to the three already described processes *metric navigation* allows for novel trajectories, especially shortcuts. For example a navigator might know the route around a big forest and now tries to directly cross the forest to reach the other side on a much shorter path. In order to do this metric properties have to be stored, i.e. angles and distances between locations. To identify a shortcut no visible landmarks indicating the goal position are permitted or the behaviour could be explained by guidance.

Mallot and colleagues. Similar to Trullier and colleagues (1997) Mallot and colleagues (Franz & Mallot, 2000; Gillner & Mallot, 1998; Mallot 1999) distinguish several processes, e.g., search, direction following, path integration or route navigation. In addition, Mallot (1999) proposed a complexity hierarchy distinguishing the processes based on the type of memory required (see Figure 1). On level one, a direct mapping between sensors and effectors occurs. This enables e.g. a female cricket to reach her chirping partner during mating (e.g., Pollack & Plourde, 1982), or a braitenberg robotic vehicle to follow a moving light source or to hide in darkness (Braitenberg, 1984). With a simple working memory (level two) sensory inputs can be integrated over time and space which allows for path integration. An ant can store a vector pointing from its current position towards the nest. During walking around this vector is updated continuously enabling the ant to return to its nest on a straight path (e.g. Wehner & Wehner, 1986). On the third level long term memory allows for learning. Landmark-based mechanisms such as guidance and recognition triggered responses are possible where certain behaviour is associated with a recognised stimulus or is derived from the discrepancy between the current and a memorised stimulus situation. Declarative memory (level four) is required to plan and to travel different routes composed of pieces and steps stored in memory. Movement decisions depend not only on the current landmark information, but also on the goal the navigator is pursuing. At the same location one can turn right in order to reach home or turn left in order to get some food. Declarative memory does not necessarily imply metric information.

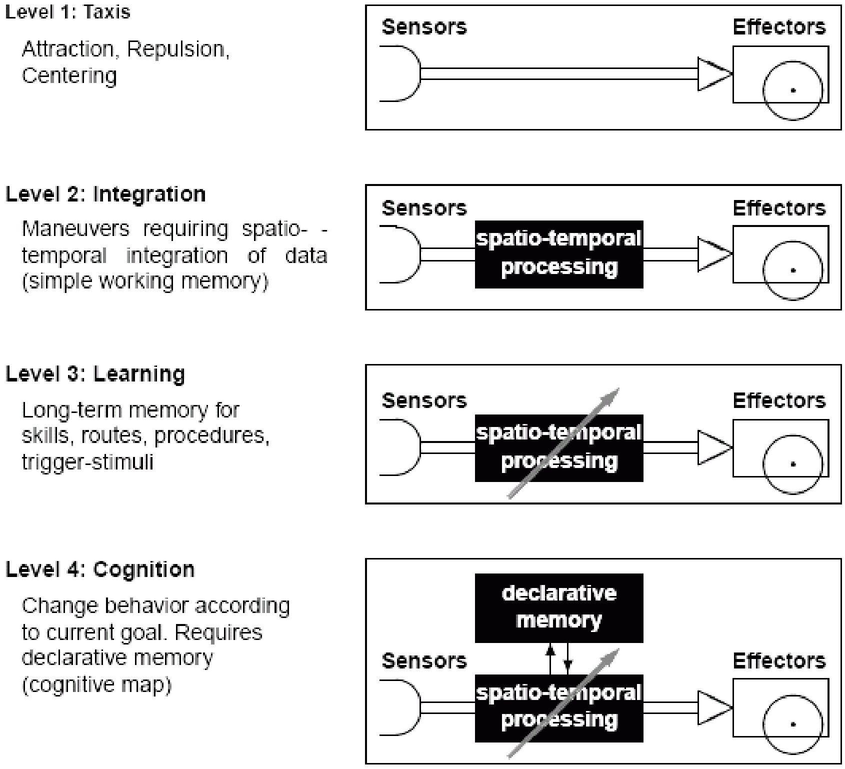

Figure 1: Four levels of complexity of behaviour according to Mallot (1999). Level 1 allows reflex-like behaviour based on the wiring of effectors and the current sensory input. Level 2 includes spatio-temporal processing of inputs arriving at different sensors and at different times. Learning is introduced at Level 3, by allowing for plasticity of the spatio-temporal processing. Except for this plasticity, behaviour is still determined completely by the sensory input. At level 4, one sensory input may elicit different behaviours depending on the current goal of the agent. The figure is taken from Mallot (1999).

Summary. Several orientation processes have been proposed. Most authors discuss path integration and what we would like to call route navigation which would encompass view-point dependent place recognition, recognition-triggered response and topological navigation. Questions relating to metric or survey navigation will be discussed in Section 2.4. Reorientation is not considered by all mentioned authors. However, research in this area is also directly relevant for the current work. In addition, many processes require a navigator to be oriented with respect to the environment, which is accomplished by reorientation. We will, therefore, discuss reorientation, path integration and route navigation in more detail.

2.3.1.2 Reorientation

As described in the goal section, we define reorientation as trying to regain one's position, i.e., location and heading, with respect to an internal or external representation of an environment. We use the same name reorientation for the goal and for the process enabling to fulfil it. Finding specific locations in an environment can be seen as measures of reorientation. Under the label 'place learning' this has been the subject of many studies in humans and especially in other animals. In this section we will focus on the process of reorientation and the cues used, rather than on the properties of the underlying knowledge. These will be discussed in Sections 2.4 and 2.5. The cues used for reorientation can be divided into the geometric layout of an environment (e.g., the shape of a room) and specific landmarks (e.g., objects in an environment).[4] We will first regard geometry and related aspects of this research and then deal with reorientation on landmarks. As research on hippocampal place cells is tightly related to this work, we will introduce this related work afterwards.

Reorientation on geometry, colour and texture: the rectangular room paradigm. In the rectangular room paradigm, subjects see an object hidden in a corner of a rectangular room and are then disoriented (for a recent review see Cheng & Newcombe, 2005). Reorientation is partially specified by the room's shape and fully specified by both the room's shape and non-geometric information, e.g. the colour of a wall (see Figure 2), a pattern on the wall or sometimes also a landmark. Subjects demonstrate their ability to reorient themselves by locating the hidden object. Rats (e.g., Cheng, 1986) and children in a small room (Hermer und Spelke, 1994, 1996; Learmonth, Newcombe & Huttenlocher, 2001) orient only on the geometry, i.e., when the object is hidden in the upper left corner of Figure 2 they search equally often in the two corners marked by a dot, but more often in these corners than in the other two corners. An encapsulated (cf. Fodor, 1983) shape based reorientation specific mechanism was proposed as an explanation (Hermer & Spelke, 1994; 1996; Cheng, 1986) and called "geometric module" (e.g. Cheng, 1986; Gallistel, 1990; see also Cheng & Newcombe, 2005). Encapsulated means that

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[4] Many authors use the term landmark also for walls and corners, i.e., features of a geometric layout. However, we restrict our use of the term landmarks to objects, e.g., trees, poles or houses in the environment.

no other kinds of information other than geometry are involved in the process, even though geometric cues might be available for other processes.

Adults generally use both geometric and non-geometric information unless they are disturbed by a verbal shadowing task where they have to immediately repeat words from a text presented via headphones. This interference does not occur during clapping a rhythm or repeating syllables (Hermer-Vasquez, Spelke & Katnelson, 1999). Hermer-Vasquez et al. (1999) assumed language to be necessary to combine geometric and non-geometric information. This assumption as well as the proposal of an encapsulated geometric module, however, is questioned by the finding that primates, birds and even fish can use geometric and non-geometric information for reorientation (Gouteux, Thinus-Blanc & Vauclair, 2001; Kelly, Spetch & Heth, 1998; Sovrano, Bisazza & Vallortigara, 2002). Also, 17-24 month old children are able to use both kinds of information in a larger room (Learmonth, Newcombe & Huttenlocher, 2001) and the shadowing effects of language do not occur when the adults receive a training trial and more explicit instructions (Ratkliff & Newcombe, 2005). Although language processes do not seem necessary, they are still helpful as there is a boost in reorientation performance within children around the ages of five and six years regarding their emerging spatial language abilities e.g. verbal expressions involving the terms “left” and “right” (Hermer-Vazquez, Moffett & Munkholm, 2001; Learmonth, Nadel & Newcombe, 2002). Another recent explanation focuses on hemispheric crosstalk as a prerequisite for combining geometric and non-geometric information (Newcombe, 2005).

When only geometric cues are available, rats and chicken seem to match local geometry such as the size of walls and the angle between walls in order to find a food source in a room with a different geometry, e.g. a rhombus, a parallelogram or a kite shaped room (McGregor, Jones, Good & Pearce, 2006; Pearce, Good, Jones & McGregor, 2004; Tommasi & Polli, 2004), rather than orient on the main axis of a room as proposed by Cheng & Gallistel (2005). They, therefore, seem to focus on local geometric cues rather than on global geometric cues.

The rectangular room paradigm was used to examine the influence of geometry, colour and language on reorientation. The next section will consider reorientation on objects as landmarks and their configuration.

Figure 2: The rectangular room with one wall painted in a different colour, as used in many experiments. Opposite corners of the rectangular room are geometrically identical. To disentangle this ambiguity the colour of the walls has to be taken into account.

Reorientation on visible landmarks. When reorienting on visible landmarks, a subject sees objects[4] from a location in a vista space. After being disoriented in order to exclude updating by path integration that vista space is entered again and the same location has to be reached based on the memory of the landmarks. This task often is referred to as place learning. In order to find a place again the subject has to reorient, i.e., to identify ones position in relation to the environment, using visible landmarks. A typical setup for rats is the Morris water maze task (Morris, 1981; Morris, Garrud, Rawlins & O'Keefe, 1982). In this task a rat swims in a circular basin surrounded by landmarks and filled with milky water until it reaches a small platform hidden under the water surface where it can rest. This platform is not visible as the water is opaque. In a test trial afterwards, the rat is put again into the pool at a random position and tries to find the platform as fast as possible. To do so the rat has to rely on memory of distal landmarks surrounding the basin.

For humans, these experiments most often were done using virtual environments, a desktop setup where participants use a mouse or keyboard to move around or an immersive virtual environment where participants can walk through a virtual environment displayed on video glasses called head-mounted-displays. In such an immersive setup participants can receive inertial cues such as proprioceptive feedback, efference copies or vestibular information which is not possible in desktop virtual realities. In a desktop version of the Morris water maze, humans learn to take straight trajectories to the platform in the presence of conspicuous distal cues unless they suffer from hippocampal lesions (Astur, Taylor, Mamelak, Philpott & Sutherland, 2002). Men perform better than women in such a task (Astur, Ortiz, & Sutherland, 1998). In general, these experiments have shown that place learning in humans can occur readily in computer-simulated environments and that such learning follows many of the principles of place learning in animals (Hamilton and Sutherland 1999; Jacobs, Laurance & Thomas, 1997; Jacobs, Thomas, Laurance & Nadel, 1998; Sandstrom, Kaufman & Huettel, 1998). In the following we will focus on the cues used for orientation in humans and non-humans.

A wide variety of species are able to reorient on visible landmarks. Bees seem to match stored visual snapshots of landmarks with their actual view: when the size of the landmark was changed between training and testing, the area in which bees searched was displaced to one where the landmark appeared roughly the same size as the training landmark when viewed from the training location (Cartwright & Collett, 1982; 1983). Contrary to bees, mice (Collett, Cartwright & Smith, 1986), pigeons (Cheng, 1988) and humans (Spetch et al., 1997) take the distance into account: e.g., they search in a constant distance from the landmark even when the size of the landmark is changed. When several landmarks are present, humans and other animals consider the configuration of landmarks in order to find a location (e.g. Collett et al., 1986; Cheng, 1988). For example if one landmark is shifted, the search position usually lies somewhere between the location indicated by the moved landmark and the location indicated by the static landmarks. Both humans and nonhumans have been shown to rely on landmarks in close proximity to a goal location (Bennett, 1993; Cheng, 1989; Cheng, Collett, Pickard & Wehner, 1987; Spetch, 1995; Spetch & Wilkie, 1994). While rodents are able to use information about landmark identity, they may principally rely on information about the geometric properties of the landmark arrangement (Benhamou & Poucet, 1998; Collett et al., 1986; Greene & Cook, 1997; Maurer & Derivaz, 2001).Birds can use both distance and directional information to find a place again, however, they seem to focus more strongly on the direction towards the landmarks than on the distance (Cheng, 1994; Kamil & Jones, 2000). Contrary to that, humans in an immersive virtual environment seem to focus more on (relative) distance than on the angle between different landmarks, unless the angles consist of right or straight angles (Waller, Loomis, Golledge & Beall, 2000). This is despite the fact that fewer distance cues are available in such an virtual environment than in a real environment. Theoretically, imprecise distance information results in a smaller area of possible locations than imprecise direction information (Waller et al., 2000). As imprecision in distance estimation increases (roughly linearly) with the distance to be estimated (for a review, see Wiest & Bell, 1985), focusing on closer landmarks should lead to better performance. For direction information this is not the case.

Contrary to absolute distances, only adult humans seem to consider relative distances. They search in the middle (or another constant ratio) between two or more landmarks when the landmarks are moved further apart. Children, monkeys, rodents and pigeons typically search in two locations about the same distance to each landmark (Collett et al., 1986; MacDonald, Spetch, Kelly & Cheng, 2004; Spetch et al., 1997). However, some birds are able to learn to search at a location that is identified by an equal distance or an equal angle towards two landmarks - at least as long as the test distances between the landmarks are within the distances experienced in training (Kamil & Jones, 1997; Spetch, Rust, Kamil & Jones, 2003).

Pigeons also seem to consider only one or two landmarks when multiple landmarks are available (Spetch & Mondloch, 1993), whereas humans in a desktop virtual environment seem to focus on the configuration of more than just two or three landmarks: contrary to removing some landmarks, removing all landmarks (Jacobs et al., 1998), removing all but one landmark (Chamizo, Aznar-Casanova & Artigas, 2003), or changing their configuration disrupts human performance (Jacobs, et al., 1998). The ability to orient on distal landmarks and on relations between landmarks develops during maturation (Laurance, Learmonth, Nadel & Jacobs, 2004).

Both birds and humans in immersive virtual environments rely heavily on the line defined by two landmarks, i.e., they are more precise when finding a location located on such a line (Waller et al., 2000; Spetch et al., 2003). This information can constrain the possible locations of the viewpoint to lie on one side of the line that connects the landmarks (Levitt & Lawton 1990; Thompson, Valiquette, Bennet & Sutherland, 2000). In an immersive virtual environment this qualitative information can also override distance information usually used. A location within three landmarks is not searched for outside of these landmarks in a different test environment, even when the location corresponding to the same relative distances as during training lies outside this enclosure (Waller et al., 2000). Here orientation on qualitative might override quantitative information. Such additional categorical encoding is also indicated in specific biases towards landmarks (Fitting, Allen & Wedell, in press) as well as in recalling locations of dots on a computer screen (e.g., Huttenlocher, Hedges and Duncan, 1991).

Both in non-human animal and human desktop virtual reality studies, the landmarks had to be visible during learning the goal location. Landmarks occluded during learning, but visible while not navigating to the goal were less helpful (Hamilton, Driscoll & Sutherland, 2002; Sutherland, Chew, Baker & Linggard, 1987). This speaks against a spontaneous integration of landmarks successively visible in two vista spaces into one coherent vista space (cf. also Sturz, Bodily & Katz, 2006).

To sum up, the available data suggest that humans and animals use multiple mechanisms for reorienting and finding places in a vista spaces. Rats have been found to switch between two mechanisms even within one trial (Hamilton, Rosenfelt & Whitshaw, 2004).

Reorientation on geometry and landmarks. When both geometric cues and landmarks can be used, reorientation focuses on geometry rather than landmarks both in rats (Benhamou & Poucet, 1998; Pearce, Ward-Robinson, Good, Fussell & Aydin, 2001; Weisend et al., 1995) and human children (Gouteux & Spelke, 2001; Hermer & Spelke, 1996). When a Morris water maze is shifted within a room with landmarks on the walls, rats search at the same location in the pool not at the same location defined by the landmarks (Weisend et al., 1995). Children reorienting in a rectangular room do not use landmarks to disambiguate between the two geometrically identical corners of the room (Hermer & Spelke, 1996). Children reorient in a room with a distinctive geometry, but not on an identical geometric figure built by identical landmarks (Gouteux & Spelke, 2001).

Geometric cues are not overshadowed. The term overshadowing refers to the finding that the presence of a second relevant cue will cause animals to learn less about a first than they would have done if trained on the first cue in isolation (Kamin, 1969; Pavlov, 1927). In animals landmarks overshadow landmark learning, but not geometry (Brown, Yang, & Di-Gian, 2003; Hayward, McGregor, Good, & Pearce, 2003; Pearce et al., 2003; Pearce et al., 2001; Wall, Botly, Black, & Shettleworth, 2004). In some cases landmark overshadowing may be explained by animals only encoding some of the landmarks which results in a lower average performance on all landmarks (cf. Spetch & Mondloch, 1993).

Hippocampal place cells. Evidence for place learning is not only found in behavioural experiments, but also in electrophysiological single cell recordings especially in rodents (e.g., O'Keefe & Nadel, 1978), but also in humans (Ekstrom et al., 2003). In these studies various electrodes have been placed in brain regions such as the hippocampus or the parahippocampus. These electrodes record the activity of a single or a few neurons while e.g. the rat is actively navigating through an environment. In the rat's hippocampus, so called place cells have been found (e.g. O'Keefe & Dostrovsky, 1971). Place cells show increased activity when the rat is located at a specific area of the experimental space no matter which direction it is facing. Also another type of neurons so called head direction cells have been identified in several areas of the brain's limbic system including the hippocampus (e.g. Wiener & Taube, 2005; Taube, Muller & Rank, 1990). These head direction cells show increased activity whenever the rat is facing a specific direction no matter where in the experimental area it is located.

The activity of place cells directly represents the location with respect to the immediate environment defined e.g. by geometry and landmarks. Place cells fire at a constant distance to the nearest walls when the shape and the size of a rectangular room is changed (O'Keefe & Burgess, 1996). When a landmark is rotated around in a circular square by 90° a place cell is active at the same area relative to the new position of the landmark, i.e., the "active area" is rotated together with the landmark by 90° (Muller & Kubie, 1987). Hippocampal place cells have been regarded as a neural correlate of a metric cognitive map (e.g. O'Keefe & Nadel, 1978). However, this only holds true for vista spaces. In environmental spaces the same place cells can be active in different parts of the environment which is the case for about 30% of all place cells (Thompson & Best, 1989). When place cells identify a specific area in an environmental space, then different cell populations should be used for different locations (Trullier et al., 1997). In two identical rooms connected via an alley a place cell can code the same relative area, e.g. the north-east corner, but also different areas (Skaggs & McNaughton, 1998). If a place cell would represent locations in environmental spaces, cells should be found with firing areas separated by a wall. In the mentioned experiment no such cells have been found. These two observations are evidence against the hypothesis that place cells code a specific area in an environmental space and therefore function as a cognitive (metric) map for environmental spaces.

However, hippocampal place cells do represent metric relations in a certain vista space. They could, therefore, be used to encode an important location in a vista space such as the platform in the Morris water task. In principal this information could be used to plan a path from one place cell area to the next until reaching the goal.

Summary. Many studies have examined reorientation, e.g., in place learning. Humans and other animals are able to profit from geometric layout as well as landmarks in order to find a location again. Geometry is considered more important than landmarks. Humans and most other animals use distances and angles to find locations again. Language eases reorientation on geometry, but is not necessary. Hippocampal place cells can be seen as a neural representation of a location in a vista space. For non-human animals reorientation seems to rely on features of specific vista spaces. Contrary to that, humans seem to be able to reorient on maps and on geometric structure of an environmental space. This will be discussed in 2.3.3.1.

2.3.1.3 Updating by path integration

Cues used for updating. We can update our position in space by path integration or by reorientation. Path integration is an orientation process in which self-motion is integrated over time to obtain an estimate of one's current position (Loomis, Klatzky & Golledge, 2001). In contrast to reorientation, path integration does not involve the recognition of external features such as geometry or landmarks (Montello, 2005). No internal or external long term representation of an environment is needed. Instead, in path integration sensory inputs indicating locomotion are integrated over time to keep track of one or more locations in the environment. Generally, working memory is seen as sufficient to do that, without the need for long-term memory (e.g., Mallot, 1999). Sensory inputs used for updating include external cues such as optic flow from the eye (e.g., Riecke, van Veen & Bülthoff, 2002) and audition (Loomis, Klatzky, Philbeck & Golledge, 1998), but mainly inertial cues are referred to when talking about path integration (e.g., Loomis, et al., 1993). Inertial cues comprise velocity and acceleration signals from the vestibular system, proprioceptive feedback from skin, joints, and muscles as well as efference copies to the limbs - centrally initiated neural commands to the musculature. There is, however, no evidence that efference copies play a role in whole-body locomotion (Montello, 2005). In non-human animals also compass information based on skylight (polarization) patterns (Wehner, 1994) and based on a magnetic sense are used to determine turning angles (e.g. Kimichi, Etienne & Terkel, 2004). In humans magnetic sensing has been proposed as a source of information, too (Baker, 1980). However, this claim lacks any clear evidence (Montello, 2005). In humans distant landmarks and slant can also provide compass information (cf. Restat, Steck, Mochnatzki & Mallot, 2004).

An impressive example for what can be accomplished with path integration is given by the desert ant (Cataglyphis). These ants leave their nest and take long and circuitous explorations for food. When they find food, they directly walk back to their nest (e.g. Wehner & Wehner, 1990). Ants are thought to compute their net distance and direction from the nest throughout their outward and return journeys and so can always return directly home from their current location. This can be described by a “homing vector” which is updated over the entire journey. If a homeward-bound ant is passively carried in darkness to a new location, it moves on a parallel path for the appropriate distance (Wehner & Srinivasan, 1981). In order to compute this vector ants use a skylight compass to estimate their turning angles (for a review see Wehner, 1997) and count their steps to estimate distances (Wittlinger, Wehner & Wolf, 2006). When homeward bound ants are placed in a jar and allowed to continue their journey after a variable delay, their ability to follow the appropriate homing vector course vanishes after a few days (Ziegler & Wehner, 1997).

Like other animals, humans can return towards the origin of a path using only inertial (vestibular and somatosersory) cues. However, even over short distances below 30 meters this path integration is quite inaccurate (Loomis et al., 1993). Physical turning is required for correct path integration. Imagined turning, optic flow or watching another person turning is not sufficient (Klatzky, Loomis, Beall, Chance & Golledge, 1998, Riecke & Wiener, in press). Nevertheless, path integration can be done based on optical flow only (Riecke et al., 2002). However, when both optical flow and inertial cues are available, inertial cues and especially proprioception seem to dominate (Bakker, Erkhoven & Passenier, 1999; Kearns, Warren, Duchon & Tarr, 2002). However, active versus passive movement does not matter in many circumstances (Klatzky, et al., 1998; Wraga, Creem-Regehr & Proffitt, 2004).

Updating processes. As mentioned, path integration is more difficult during imagined movement compared to physical movement especially for rotations (Klatzky et al., 1998; Rieser, Guth & Hill, 1986; May, 2004). This fact can be explained by different processes. The necessary transformation could be facilitated by physical motion (cf. Farell & Robertson, 1998). Alternatively, interference could occur from a conflict between the awareness of one’s physical position in an environment and the discrepant position one has to adopt in imagination (May 1996; 2004). This interference theory is supported by results showing disorientation to improve the performance in imagined rotations (May, 1996). Mere facilitation of the necessary transformation by physical locomotion could not explain this. The interference theory can also be applied to navigating virtual environments. Here the real and virtual world can interfere to stronger or smaller extents depending on the quality of the virtual reality setup, e.g., desktop versus immersive setups, the field of view, etc. (e.g., Riecke, Cunningham & Bülthoff, 2006; Schulte-Pelkum & Riecke, in press).

Updating by path integration when moving physically often seems to happen in an automatic manner: Participants can update very accurately and easily, without any awareness of having to think about the task (Rieser et al. 1986; Rieser, 1989). Participants are even unable to voluntarily refrain from updating when moving physically (Farell & Robertson, 1998; Farell & Thomson, 1998; May & Klatzky, 2000; but see Waller, Montello, Richardson & Hegarty, 2002). However, for imagined environments we are able to refrain from updating, even if we move physically (Wang, 2004).

What is updated in path integration. Single locations can be updated by path integration, e.g., the start of a route in a homing task (Loomis, et al., 1993). Also multiple locations are updated such as the corners of a room or an array of objects (e.g., Wang & Spelke, 2000; Holmes & Scholl, 2005). Not only environments seen before can be updated by path integration, but also unknown environments described by language (Avraamides, 2003; Loomis, Lippa, Klatzky & Golledge, 2002), or an object array on a table explored haptically (Pasqualotto, Finucane & Newell, 2005). Familiar environmental spaces such as a university campus can also be updated during physical rotations and imagined translations (Easton & Sholl, 1995; Holmes & Sholl, 2005).

Updating on longer routes and storing routes in memory. Due to its integrative nature, path integration is necessarily prone to the accumulation of random errors (Wehner, 1999), especially when only relying on inertial cues (Benhamou, Sauvé & Bovet, 1990). This is empirically shown in ants who determine the origin of their journey increasingly less accurately the farther they have ventured out from the start (Wehner & Wehner, 1986). Most studies on human path integration only considered routes shorter than about 30 meters (e.g., Loomis et al., 1993). For exploring environmental spaces such as houses or cities usually much larger distances have to be covered. For such spaces, path integration based on inertial cues probably plays only a minor role, if at all: correct inertial cues as during a car ride do not enhance spatial knowledge compared to no or wrong inertial cues while watching a video of that ride. However, full field of view and the ability to turn ones head do enhance one's spatial knowledge in such situations (Goldin & Thorndyke, 1982; Waller, Loomis & Steck, 2003). Estimates of the time travelled may be more important for travelling longer distances than path integration.

In the previous text, updating referred to keeping track of one's position relative to a location or an environment. This can be explained by working memory. However, also the velocity profile of a translation can be stored in memory (Berthoz, Israel, Georges-François, Grasso & Tsuzuku, 1995). In triangle completion experiments participants also seem to maintain a history of the routes travelled: latencies increased for more complex trajectories which should not be found when only storing a homing vector (Loomis et al., 1993). Even ants and bees store information about where a food source is to be found (Collett, Collett & Wehner, 1999; Srinivasan, Zhang, Lehrer & Collett, 1996). For long term storage of paths learned by inertial cues the encoding-error model (Fujita, Klatzky, Loomis & Golledge, 1993) might be appropriate. This model assumes that people encode the distances and turns of a route travelled. Pointing or homing errors errors reflect systematic inaccuracies in the encoding process, as participants can compute and execute pointing movements and walking trajectories without any systematic error. It was originally developed to explain online updating by path integration, but was not supported in its original form (Klatzky, Beall, Loomis, Golledge & Philbeck, 1999, Riecke et al., 2002). It might, however, explain pointing to unseen locations from memory. To imagine standing at a location and use long-term memory of a route to compute the direction of another location is an alternative solution for many imagined updating studies (May & Klatzky, 2000; see also Amonrim, Glasauer, Corprinot & Berthoz, 1997; Avraamides, 2003). Two alternative processes can, therefore, explain results from updating by path integration: First, online updating of one or more locations in the environment relying only on working memory which happens obligatory during physical motion and, second, accessing trajectories stored in long term memory and imagining the goal to point or to walk to. In an abstract form this knowledge can be described by a chain of vectors, which means not preserving the velocity profile, but simply the angles and distances from a position. The latter process probably is limited to human orientation, as is imagined updating in general.

Summary. Path integration is an orientation process in which self-motion is integrated over time to obtain an estimate of one's current position in space. When moving physically, updating happens automatically and leads to better performance especially when turns occur. Interference can explain the drop in performance for imagined updating compared to physical updating as well as problems with virtual environments. Online updating by path integration is an error prone working memory process. In humans accurate updating is limited to rather short distances. Movement trajectories can also be stored in long term memory.

2.3.1.4 Route navigation

Route navigation is a wayfinding process, a process enabling us to reach a known goal in an environmental space, by navigating a known route. The knowledge necessary for route navigation is called route knowledge (see 2.4.2). It can be learned directly by navigating a route or indirectly via, e.g., maps or verbal directions. We will propose a theoretical framework for route navigation including elements and sub-processes necessary for executing route navigation.

Route navigation as we understand it involves two parts: first, identifying a location, and second, moving towards the goal (although not necessarily directly). The latter involves selecting one among several possible directions to move towards. These two parts form the basic element in route navigation. In order to reach a goal several of these basic elements have to be combined, i.e., several locations have to be identified, and a direction has to be selected at each location.

Identifying a location. To reach a goal by route navigation a navigator has to identify the start, the goal and several locations inbetween where correct route decisions have to be choosen. These locations can be identified in various ways.

For example one could identify the specific form of an intersection, recognise a familiar landmark, e.g., a yellow house, or one could identify a location by counting, e.g. the third intersection as described in route directions or displayed in a map. As the examples demonstrate, for human navigators such locations do not have to be visited before, but can be learned from other sources. If a location was visited before and is recognised during route navigation, probably the same cues described for reorientation play a role, too (cf. 2.3.1.2). These cues can comprise proximal and distal cues (Steck & Mallot, 2000). Cue usage will depend on cue saliency. A cue which is commonly encountered in an environmental space is not very specific for a location also referred to as as not very salient. Such a cue is used less often than a salient cue which encountered less often (cf. Stankiewicz & Kalia, in press). From a theoretical point of view only locations have to be remembered where alternative route choices could occur. When a route only goes straight on without any route alternatives, one does not have to think about where to go. Consequently participants are better in remembering information from decision points: in familiar environments, on routes in virtual environments, routes displayed on a map, and routes presented via slides landmarks are mentioned more frequently and are recognised better when located at decision points (Aginsky, Harris, Rensink & Beusmans, 1997; Appleyard, 1969; Cohen & Schuepfer, 1980; Janzen, 2006; Lee, Tappe & Klippel, 2002).

Route navigation relies on discrete locations, not on a continuous representation of the environment (Mallot, 1999; Trullier, et al., 1997). How the discrete locations emerge from a continuous perceptual input when navigating through an environment is largely an open question. We can however say something about the extension of such a location. We want to define a location referred to in route navigation as an area that a navigator is also able to reorient oneself. Defining such an area as the area where a navigator selects the same action (Trullier, et al., 1997) is problematic, because it can lead to circular explanations. For example a navigator turns left exactly at that area which is defined by the navigator turning left.

When identifying a location during route navigation, a navigator is oriented, knowing where the last location visited is situated. This distinguishes route navigation from reorientation where one does not know one's location on a map or with respect to familiar locations. If a navigator gets lost during route navigation he or she has to reorient before being able to navigate the route towards the goal again. For short distances, recognizing a familiar location might be substituted by path integration, e.g., walking in darkness to the next room. However, this will be an exception.

Directional information in route navigation. After identifying a location the navigator has to select a direction to move from the current location, in order to reach his or her goal. This might include approaching a visible landmark, also called beaconing. Offered as the only possibility by Wang and Spelke (2002) to navigate from one location to another, beaconing might be as simple as following an extended landmark such as a wall, but most often involves locomoting in a certain direction in relation to one or to several landmarks (guidance). Selecting a direction to move towards always involves moving away from the current location. This distinguishes route navigation from reorientation, where finding a location in vista space is usually the measure for knowing one's position with respect to the environment. Contrary to that, route navigation points away from the current location along a route leading towards a known goal that is not directly accessible. This route, and therefore also the selected direction, does not have to lead straight to the goal. The route can involve a loop if, e.g., no other route is possible or known.

For determing the direction to move towards Trullier and colleagues and Mallot and colleagues propose an associated behaviour, a triggered response. A specific triggered response might, however, not explain all observed behaviour. Rats swim a route learned by walking (MacFarlane, 1930). Cats walk a route learned while being passively carried along the route (Hein & Held, 1962). We can cycle a path learned by walking or learned from a map. The direction information, therefore, has to be more abstract than a specific behaviour such as walking or cycling.

The direction to move towards will also not be egocentric in general: often rats walk into a specific corridor in order to get food, even when they learned to turn left in order to get the food, but in the test trial have to turn right (Restle, 1957). The direction information, therefore, is more likely a direction in relation to the current environment rather than a direction in relation to ones current body orientation, which typically is the case for path integration.[5] In the following we would like to describe this direction information by a vector pointing into the direction indicating where to move next. Note that this applies for route navigation in familiar environments experienced directly, which is the case for all non-human animals. Humans also can navigate using maps and verbal route directions. Here left/right decisions within an egocentric reference frame probably play a more prominent role.

Combining basic elements. Locomoting into a direction at one specific location normally is not sufficient to reach a goal. It has to be done several times- the basic element of identifying a location and selecting a direction has to be recombined to get a chain of these elements. Hereby the navigator learns how to get from one location to another, e.g., "walking this street I will reach the city hall next". Such a sequence of identifying a location and deciding where to go does not have to be specific for a certain goal. Rats can latently learn the structure of their environment, e.g., learn the route to a room without getting food in that room, but getting food somewhere else. When they are put into the room directly, find food,

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[5] This does not imply that the memory used for route navigation is accessible equally well from every orientation (cf. 2.4.5).

and are put to the start again, they immediately approach the room (Blodgett, 1929; Tolman & Honzik, 1930). They must have learned the route to the room before, even there were not rewarded for doing so. Rats also use the shorter one between two previously explored alternative routes when the route used before is blocked (Tolman & Honzik, 1930). This does not necessarily involve survey knowledge (cf. 2.4.2 and 2.4.3).

Using an alternative route spontaneously indicates that rats learned how to get from one location to another independently from a goal. It also shows that rats can learn multiple, interconnected routes and can even choose the shortest one among two alternatives. So not only single chains of navigational selections, but a whole network can be remembered. Such a network can be described by a graph (e.g., Mallot, 1999; Trullier et al., 1997). We propose that the nodes of such a graph represent locations and the edges represent vectors pointing from one location in the direction of where to navigate next in order to reach the next location. The location that the vector points towards does not have to be the direction the next location is situated. It is sufficient to give just coarse direction information which could be followed, e.g. by a long winding road leading to the next location with more route alternatives. Ants and bees, e.g., move a short distance into a specific global direction when encountering a familiar landmark (e.g. Collett, Collett, Bisch & Wehner, 1998; Menzel, Geiger, Joerges, Müller & Chittka, 1995). If a vector would point exactly to the next location, shortcuts between locations could be computed principally. This would then be regarded as metric navigation and not as route navigation.

In order to navigate from the current location to a goal in the environment, a navigator has to select a sequence of navigation instructions leading to the goal. This could be explained by a symbolic search algorithm operating on such a graph, e.g., iterative deepening search where all paths from the start with a certain number of edges are generated and the number of edges is increased step by step until the goal is reached by a path (Russel & Norvig, 1995). Several such symbolic search algorithms have been introduced. However, the same results can be achieved assuming the subsymbolic process of activation spread which does not require the representation and manipulation of symbols. It is, therefore, much more plausible to occur in animals. In such a process, activation spreads out from the node representing the current position and/or from the node representing the goal. The activation of a node will be the lower the further it is away from the current location and/or the goal. A mechanism which then selects the sequence of nodes between start and goal with the highest activation can provide similar results as symbolic search algorithms. In general such a mechanism would always select the route with the fewest number of nodes. It can, therefore, explain identical behaviour without assuming symbolic planning processes (cf. Trullier et al., 1997).

Summary. We provide a specific concept of route navigation as a wayfinding process which allows reaching a goal in an environmental space by a travelling a known route. It involves identifying a location in the environment and then selecting a direction along a possibly looped route leading to the goal. Identifying a location and selecting a direction is repeated several times before a goal is reached. Route navigation is based on discrete locations, not on a continuous representation of the environment. It is not learned for one certain goal, but location to location information is learned. This can constitute a network structure of locations connected with 'move-to-information'. The where-to-move part is an abstract direction information, e.g., expressed by a vector, rather than a specific behaviour. The knowledge necessary for route navigation is called route knowledge and can be learned by directly experiencing an environment or indirectly via maps, verbal descriptions etc.

2.3.1.5 The relation between reorientation, path integration and route navigation

When talking about the relation between navigation processes several interrelations are possible (Cheng & Newcombe, 2005; Wang & Spelke, 2002). The most basic relations are independence and interaction. If the two processes are independent they rely on specific input and guide behaviour in a specific way without interacting with the information processing of the other process. The processes can then be called modules (cf. Cheng, 1986; Fodor, 1983). In situations where two such processes run in parallel and would result in different behaviour, e.g. search for an object at different locations, only one process can determine behaviour, as we can only search at one location at a time. One process has to overwrite the other process.

If two processes are not independent, but interact, they share information properties (cf. Cheng & Newcombe, 2005). Both processes can build different memory representations, but take memory from other sources into account. Or the processes rely on different sensory inputs, but build more or less integrated memory representations. The last case would be that the two processes rely on the same sensory inputs, and construct similar memory contents. Even if both processes contribute to the formation of spatial memory in such a way, they can use this memory in other ways which results in different behaviour. In all three cases the resulting behaviour could be determined by one process alone (overwriting the other process) or by a fusion of the behaviours which would result from the processes alone. A fusion would mean to search somewhere inbetween the two locations indicated by process one and two.

From the point of observable behaviour one has to distinguish between overwriting and fusion of behaviour. If fusion is observed, both processes have to interact somehow. If one process overwrites the other one, they could be completely independent, but could also share information. In the following we will look what relations between reorientation, path integration, and route navigation are plausible.

Reorientation and path integration. Reorientation on visual cues overwrites online path integration. Imagine walking a few meters in a room with closed eyes. Due to path integration we have a feeling about where the entrance of this room is located relative to us. However, when we open our eyes again and see the entrance in another location, we do not assume the entrance at the 'old' location indicated by path integration any more, but immediately shift the location of the entrance to what we see. When both processes can be applied, we estimate a location relative to us based on our visual input, not on path integration.

The same relation is found when learning a location by path integration and visual input where both cues conflict: In an immersive virtual environment participants do not learn the trajectory to a location by path integration when several identical poles are provided which change their location from learning trial to learning trial (Foo, Warren, Duchon & Tarr, 2005). Participants seem to orient on the visual input which keeps changing in this study and does, therefore, not help them. Again, reorientation overwrites path integration.

Route navigation and reorientation. Reorientation and route navigation differ in the goal to be achieved. In reorientation a navigator is disoriented and wants to orient again. For route navigation a navigator has to be oriented initially. Both processes as we define them here cannot be active at the same time and therefore they cannot overwrite each other. They can, however, rely on the same memory structure. When the geometry and/or the configuration of a specific vista space are recorded, this can be used to find a place within that space. A vector pointing from this vista space into a direction enables navigating a route. Mathematically this vector also defines a location outside this vista space. It can be seen as equivalent to a location within this vista space which was learned during a place learning experiment.

Route navigation and path integration. Route navigation overwrites path integration. At familiar landmarks desert ants as well as bees move into a specific direction (Collett et al., 1998; Menzel et al., 1995). During that time the ant's global homing vector is updated, but is not guiding behaviour. Afterwards the ant orients on the global homing vector again unless encountering other familiar landmarks. (Collett et al., 1998). Also bees orient on shifted landmarks (Srinivasan, Zhang & Bidwell, 1997). So even ants and bees with their highly sophisticated path integration abilities (cf. 2.3.1.2.2) rely on route navigation rather than path integration. To the author's knowledge no study directly compared path integration with landmark navigation in humans. However, when humans make a shortcut between two locations learned by path integration and stored in long term memory, they rather orient on replaced landmarks on this route than on the correct path indicated by path integration (Foo et al., 2005). So route navigation likely overrides path integration when both can be applied. At least for ants and bees path integration can be seen as a backup-process when route navigation is not available (Collett & Collett, 2000).

When both are in conflict, route navigation overwrites path integration. It is, however, possible, that information from path integration is stored in long term memory and is used for route navigation. A vector pointing from one location to another and not just somewhere in the direction of travel could be derived from path integration. This would allow for shortcuts. In that sense path integration could provide the glue for connecting locations used in route navigation (cf. Loomis, Klatzky, Golledge & Philbeck, 1999).

2.3.2 Strategies

2.3.2.1 The difference between processes and strategies, human and non-human navigators

We described three processes applied by humans and other animals in order to achieve their goals. Are there, however, also mechanisms specific for human orientation in space? According to Wang and Spelke (2002) encapsulated representations of the environment act as building blocks for the three processes they assume. In addition, specifically human symbolic capacities enable to construct new spatial representations and strategies to overcome the limits of the more primitive navigational systems. So humans additionally build other, namely symbolic, representations of their environment. They apply strategies on these new representations maybe also on the existing representations which are encapsulated and therefore do not interact. Trullier and colleagues (1997) only consider animal navigation. For Mallot (1999) elements on one navigation level, e.g., recognition-triggered response can act as building blocks on a ‘higher’ level, e.g., using declarative memory. He does not propose a clear distinction between human and non-human navigation.

So far symbolic processing has been proposed being specific for human orientation. In the broader sense of what distinguishes humans from non-humans many concepts have been proposed e.g., rationality, self conciousness (Plessner, 1928; Scheler, 1928), or intentionality (Tomasello, 1999) just to mention some. This discussion began as early as the 5th century B.C. (Protagoras cited in Platon Theaetetus, Section 152a) and has not yet found a solution commonly agreed upon. As for orientation in space we propose especially two capabilities specific to humans which allow for a much more flexible orientation. These capabilities concern the representations used for orientation as well as orientation mechanisms: First, using other internal and external representation formats in addition to those used by non-human animals. Second, being able to plan in the sense of searching a ’space’ of possible solutions. These are mere suggestions.

They probably are not exclusive, however, we think they are crucial. We will explain them in more detail and refer to them in the discussion again.

Using other representational formats. Like Wang and Spelke (2002) we assume that processes such as path integration use specific representations, e.g., a homing vector in path integration, although we think that these representations do not have to be encapsulated (cf. 2.3.1.5). These representations evolved in order to support spatial orientation and are basically used for that purpose. Contrary to animals, we think that humans are able to leverage representation formats which probably did not evolve originally in order to support orientation in space. The most important one is language. Humans can give verbal directions, they can describe a location, and find a location with only a verbal description, e.g., addresses are used for that purpose. In verbal format, humans are able to communicate these descriptions of space to other people, which is much more flexible than, e.g., the vector information communicated by bees (von Frisch, 1967). Humans are also able to represent spaces in pictorial format on paper, i.e., draw maps. These external representations are a widespread means to store and communicate information about space. Maps can also be used for planning. Using a map we do not plan our further route based on our probably error prone spatial memory, but we use an external representation for that which can be more efficient (cf. Scaife & Rogers, 1996). As we explained in 2.1 we regard maps as a figural space which is distinguished from vista or environmental spaces which surround us. In order to use maps for orientation we have to translate them from figural space to vista or environmental space (cf. 2.4.5).

Both language and maps can be used as an external representation to unburden our internal memory. In that way they can also ease planning. Both can be used for communication which they share with gestures. However, we can also memorise maps and verbal directions as such. In that way we apply different internal memory systems in order to store environmental information. To use such memory then for reorientation or wayfinding, we assume that transformation processes are necessary.

Planning. We consider the planning of a route also as a specific human capability as opposed, e.g., to an activation spread mechanism (cf., 2.3.1.2.3). Planning in our sense can be described as problem solving or more specific searching a route through a search space (cf. Anderson, 1995; Russell & Norvig, 1995). The search space consists of the possible states, e.g., the possible locations or positions (locations and headings) in the physical space. Actions change the current state mainly by moving from one possible location or position to another. The result of such a search is a route which afterwards can be navigated. This search entails 'as-if actions', i.e., to imagine what would happen if I would do that. The search can be performed on representations provided by existing orientation processes, e.g., route navigation. Here locations could be imagined and as-if actions could take one to the next remembered location. Taking metric information into account, this could result in a shortcut. The search could, however, also be performed on the external representation of a map.

We cannot rule out that planning mechanisms are also used by animals. We think, however, that there are simpler explanations than planning that could explain, e.g., route choice in animals (cf. 2.3.1.4.3). In addition, there are severe limitations in animal navigation such as the lack of clear evidence for novel shortcuts (see 2.4.3) which would be plausible when being able to apply as-if actions. We will call these specific human mechanisms which involve planning 'strategies' as opposed to 'processes' that are belived to also be used by other animals.

Most of the strategies applied do not search the whole problem space, i.e. all possible states and the action sequence used to reach them. These heuristics try do find simpler solutions, but are not necessarily successful in doing so (cf., Strube, 1996). We will describe several strategies for reorientation and selecting routes on maps and in environmental spaces in the next sections. The question about the knowledge required to perform these strategies and different representations applied for wayfinding strategies will be discussed in more detail in Sections 2.4 and 2.5.

2.3.2.2 Reorientation strategies

As indicated in 2.3.1.2 reorientation mainly works by recognising a salient vista space. If we recognise a unique landmark, we know where we are. Recognition in this sense is a rather automatic process and does not involve any cognitive reasoning, let alone specific strategies. Also the usefulness of language when orienting on ambiguous geometry does not necessarily imply the involvement of strategies. Additional verbal encoding such as "on the left side" is sufficient to explain this advantage. For reorientation in unfamiliar environments with respect to a map there are some specific human approaches such as using a GPS signal or the street name. Doing so, however, does not involve strategies so much either, except maybe for how to find the street name or the coordinate on the map. When reorienting in environmental spaces without using unique indices such as landmarks, street names or GPS signals, strategies can be applied. Generally, this is considered a rather difficult task (Pick et al., 1995; Stankiewicz, Legge, Mansfield & Schlicht, 2006; Warren, 1994). It can be described by hypothesis testing where features of the current view and maybe also the movement history are matched with features in memory of the environment or with features in a map of the environment (cf. Warren, 1994; Thompson, et al., 2000). The larger a virtual environment intensively learned from a desktop the more possible positions have to be considered and the longer it takes to reorient and navigate to a location within that space compared to an ideal navigator (Stankiewicz, et al., 2006). Providing a map of such a very familiar environment does not enhance performance, however, highlighting all possible locations in that map does. Given a picture, localising one's corresponding position in a map of a downtown area is easier with a tourist map showing buildings in perspective view and, therefore, providing more features to match than a standard birds-eve-view map (Warren, 1994). Experienced map readers match features and feature combinations to localise their position in a topographic map of an open hilly landscape, i.e., a large vista space (Pick et al., 1995). Qualitative rather than metric features and their relations are used for such a reorientation task, e.g., order is used rather than exact distances. Successful strategies taken from verbal protocols focus on environmental features rather than map features, orient on two points in the line of sight and on points near one's position, imply hypothesis testing, and changing ones viewpoint.

From a computational point of view reorientation by individual feature matching is more robust and less vulnerable to noise than trying to match whole scenes (Thompson et al., 2000). From the features used to reorient in a desktop virtual reality, participants seem to rely more strongly on geometry than on landmarks. And they seem to take saliency of the features into account (Stankiewicz & Kalia, in press). They recall geometric cues better than landmarks. More informative landmarks, i.e., landmarks encountered on fewer locations, are recalled better than less informative landmarks. Performance in determining one's position in a map is better based on pictures with distinctive features such as non-rectangular geometry (Warren, 1994).

2.3.2.3 Wayfinding strategies

A vast amount of strategies for wayfinding have been proposed. We describe a selection of strategies referring to theoretically important issues or those with an empirical base. No strategy referring to free exploration or uninformed search (e.g. Darken & Siebert, 1996) will be mentioned. These latter strategies do not correspond to wayfinding in the sense used here. When always walking along one wall in order to search for the exit of a maze we do not know the exit beforehand and do not hence perform wayfinding in the sense used here. Table 1 shows an overview of the strategies mentioned.

When using wayfinding tools such as route planners the most people want to get the route with the *shortest distance* or the *shortest time* to travel. In order to do so, the whole search space must be considered. Therefore, it is necessary that a good knowledge of the environment is either acquired directly over a long time or by using a map. For example shoppers on their way back from the first shop were found to locally minimise the distance between the multiple goals they are to visit by walking to the nearest neighbour (Gärling & Gärling, 1988). Generally, selecting the shortest route is appropriate for computers. This is probably also the strategy most often used in artificial route planning systems. Humans, however, are more restricted in their capacity to track multiple possible solutions and are,

Strategy	Applies to whole route	Information required	Requires metrical knowledge
Shortest distance/time	yes	very familiar or map	yes
Fewest number of turns	yes	very familiar or map	no
Defer path choice	no	very familiar or map	no
Hierarchical strategy	yes	very familiar or map	no
Initial segment	no	initial segments of alternatives	yes
Least angle	yes	location and distance to goal	yes
Edge following	no	goal is on edge	no
Cautious shortcutting	no	shape of route to be shortcutted	no
Familiar routes	yes	one possible route to goal	no
Memory access	yes	very familiar	no

Table 1: Summary of the wayfinding strategies mentioned.

therefore, more likely to go for a satisfactory solution rather than an optimal one (cf. Gigerenzer, 2000).

Golledge (1995) proposed the strategy of choosing the path with the *fewest number of turns*. Assuming at turns there is a potential risk of getting lost, this strategy should lead to fewer errors. Applying this strategy requires good knowledge of the environment or a map.

A related strategy is called *defer path choice* (Christenfeld, 1995). Once people are travelling in one direction they turn at the last possible point. This was shown in route choices on maps, in vista, and in environmental spaces where the route alternatives where identical with regard to length and number of turns (Christenfeld, 1995). This strategy is one possible explanation for asymmetries in path choices on the way out and back found both in maps and real environments (Golledge, 1995; Stern & Leiser, 1988).

In a *hierarchical strategy* a navigator first tries to get to the target region before doing a fine-tuned planning there. This was shown for several virtual environments with identical path lengths (Wiener & Mallot, 2003). Applying a hierarchical strategy minimises the overall search space and hence the cognitive load. It requires good knowledge of the environment including a hierarchical structuring or a map providing this information.

In the *initial segment* strategy the path is chosen which begins with the longest straight segment. From several routes printed on a map people prefer the route which is initially straighter, regardless of what later proportions (Bailson, Shum &

Uttal, 1998; 2000). This hill-climbing strategy is also applicable with only sparse knowledge of the environment or just from current visual input.

In the *least angle* strategy people try to minimize their global deviation from the direction of the goal position (e.g., Hochmair & Frank, 2002). To apply this strategy the direction and distance of the goal with respect to the current position has to be known. It can be considered as a hill-climbing strategy with respect to angular deviation.

Another strategy requiring only little knowledge is *edge following* (Hutchins, 1995). When a destination lies along an edge such as a river, a street or a coastline, we can follow the edge to our destination.

If we know the shape of the edge, e.g. making a large circle leftward we can try to make a shortcut by leaving the edge to the left. In doing so, it is advisable not to go too far to the left. As the edge which can be a familiar route is to the right we cannot get lost, when walking too much to the right, because we will encounter the edge at one point. We don't have such a security belt when navigating too far to the left. Such a strategy could be called *cautious shortcutting.* It allows for shortcutting with only sparse or even no metric knowledge.

A last strategy comprises taking *familiar routes* as often as possible. If an environment is not known very well, sticking as much as possible to familiar paths is likely to reduce errors even when shorter routes are possible. The familiar routes strategy has to be distinguished from choosing always one route in a very familiar environment, where no planning is involved and just memory is accessed.

In daily life, one concrete path choice often can be explained by various strategies. For example choosing the long side first when walking around a bookshelf can be explained by the initial segment strategy, the defer path choice strategy and the least angel strategy. This has to be taken into account when trying to compare different path choices.

Route choices strategies can differ between individuals as well as between different environments or different tasks within one individual. Men report focusing stronger on configurations as used in a least angle strategy, whereas women report focusing more on properties of the route (Lawton, 1994; 1996; Lawton & Kallai, 2002). Participants rely more often on the least number of turns when the environment follows a grid layout than when the environment consists of diagonal or curvilinear streets (Golledge, 1995). In maps and real environments participants choose different routes on the way out and back (Golledge, 1995; Stern & Leiser, 1988). Route selection criterias are also different for planning a route directly between start and goal compared to planning a route via a third location (Golledge, 1995).

As already mentioned, one important requirement for the selection of a certain strategy is the required knowledge (e.g., Stern & Leiser, 1988). To apply a least angle strategy, one has to know the distance, and direction of the goal. To apply a least turn strategy, one has to know the turns on all route alternatives. To finaly select the shortest distance, one has to have a precise knowledge about the distances. Different strategies require different knowledge. The kinds of spatial knowledge and their distinction, transformation, biases, and development are discussed in the next section.

2.4 Spatial knowledge

We orient in space in order to fulfil our needs such as getting food, having fun or earning money. We find our way to such locations visited before or communicated to us and we reorient after getting lost. Several orientation mechanisms enable that. These mechanisms rely on sensory input and on knowledge about the environment. Approaching a visible target or updating a location in the environment by path integration, e.g., the entrance to a building, do not rely on long term memory of an environment. However, to reorient and especially to reach a goal we have to rely on knowledge either stored in long term memory or available to us via other representation, e.g., language or maps. Specific mechanisms require specific knowledge, e.g., a least angle strategy requires knowledge about the direction and the distance of a goal. This section will look at this knowledge in more detail. As mentioned we acquire spatial knowledge from several sources (2.4.6). This knowledge can be freshly acquired or well established through extended experience (2.4.1). It can comprise individual locations (landmark knowledge), information how to get from one location to another (route knowledge), and metric relations such as directions and distances between locations (survey knowledge, 2.4.2). The locations can be memorised with respect to various frames of reference, e.g., with respect to our current position in space or with respect to other locations (2.4.5). It is a question whether this knowledge is integrated into a coherent "cognitive map" or it consists rather of individual pieces connected with each other (2.4.3). Our knowledge does not represent all aspects of a physical space, it is an abstractly representation. Therefore, inaccuracies necessarily occur. These inaccuracies are not random in nature, our knowledge is systematically distorted (2.4.4.).

All these questions and distinctions look at spatial knowledge from a certain perspective. These perspectives, however, are not independent from each other. One experiment can be interpreted from several perspectives. For example acquiring spatial knowledge from a map also means to deal with newly acquired knowledge which is provided in a map-based reference frame and comprises route as well as survey knowledge. Results from such an experiment can and will be interpreted from several perspectives. Redundancies are, therefore, unavoidable, but necessary to explain the different conceptions of spatial memory.

This section regards spatial knowledge as content with specific attributes that can be distinguished. It is not as concerned with the format of the representations. This will be concerned in 2.5.

2.4.1 Familiarity

2.4.1.1 Effects of familiarity

Knowledge can be distinguished by how well it is established (e.g. Anderson, 1995; Reason, 1990). If we know something very well such as the area we grew up, we can access this information very rapidly and easily. We do not make many errors, e.g. we know immediately how to walk home without getting lost. The knowledge is reliable and does not change very much, it is stable. We also do not think much about using this knowledge, or applying this or that strategy. We just know what to do. Contrary to that, newly acquired knowledge, e.g., after moving to a new city changes a lot: we encounter new streets, explore surprising shortcuts etc. Often the knowledge is not sufficient so we get lost or we have to apply a certain strategy, e.g., follow a complicated route as we do not know another one. Some times this knowledge is mainly acquired via maps. In experimental research this corresponds to a memory paradigm. One learns an environment, e.g., via a map and then has to perform a task which requires this newly acquired memory.

Many studies have shown the relationship between familiarity with an environmental space and performance in orientation tasks such as map drawing or real and imagined pointing and distance estimation (e.g., Evans, Marrero & Butler, 1981; Gärling, Böök & Ergezen, 1982; Herman, Kail & Siegel, 1979; Kirasic, Allen & Siegel, 1984; Montello, 1991).

Familiar participants perform better, because they rely on more and often better knowledge. It has been proposed that survey knowledge which concerns metric relations depends on familiarity (e.g., Siegel & White, 1975). We will discuss this claim in 2.4.2.

2.4.1.2 Orientation-dependency

Another discussion looked at orientation dependency in knowledge about familiar and unfamiliar environments. An orientation-dependent memory representation is stored in memory and accessed preferentially in a single orientation; an orientation-independent representation is equally accessible in any orientation (e.g., Montello, et al., 2004). Knowledge of environmental spaces acquired in direct experience is generally orientation-dependent for unfamiliar environments and orientation-independent for familiar environments, i.e. in familiar environments performance measures do not depend on the real or imagined heading in the environment (e.g., Evans & Pezdek, 1980; Sholl, 1987; Rossano, West, Robertson, Wayne, & Chase, 1999).

Two explanations for the change from orientation-dependent to orientation-independent performance have been proposed. First, the knowledge itself changes from orientation-dependent to orientation-independent. Second, we just acquire more orientation-dependent bits of knowledge or views in different orientations so that we always find a stored view that is adequate or we can interpolate between two stored views.

This question is similar both for figural spaces (e.g. Biedermann, 1987; Bülthoff & Edelmann, 1992; but see Hayward, 2003) and environmental spaces. Objects are better recognised when oriented in the perspectives they were encountered (e.g., Tarr, 1995). Even more than other objects faces are better recognised when presented upright than when presented upside down (Yin, 1969). Similarly, maps are seen mainly from one perspective only, i.e., usually north up. Knowledge acquired from maps is also orientation-dependent. For example participants point better to locations when imagining looking northwards compared to imagining looking towards other directions (Sholl, 1987; Werner & Schmidt, 1999). Orientation-dependence is found both in newly learned maps and in highly familiar maps (e.g., Evans & Pezdek, 1980). Performance decreases linearly with larger angles between experienced and tested orientation (Evans & Pezdek, 1980). As with other objects familiarity alone does not seem to lead to orientation-independent knowledge. However, orientation dependency attenuates when experiencing multiple views of a map (Lloyd & Cammack, 1996; MacEachren, 1992, Tlauka & Nairn, 2004). However, when experiencing multiple orientations, performance might still be best for a view encountered at the beginning of the learning phase (Tlauka & Nairn, 2004).

For vista spaces similar effects have been found. When learned from only one perspective, performance when oriented along this perspective is usually better (e.g., Roskos-Ewoldsen, McNamara, Shelton & Carr, 1998; Shelton & McNamara, 1997; Waller et al., 2002). Generally, performance decreases linearly with larger angles between the experienced and the tested view. This linear degradation is the case for learning one or learning multiple views (Diwadkar & McNamara, 1997; Iachini & logie 2003). These results indicate an encoding of single or multiple views of an environment, at least during early stages of learning. During later stages, an orientation-free representation might form or it might exist from the beginning, but not play a relevant role until later stages. In some studies the advantage for familiar views did not become significant (Presson & Hazelrigg, 1984; Presson, DeLange & Hazelrigg, 1989). This lack of difference might stem from updating processes or from focussing on accuracy while ignoring latency (cf. Waller, et al, 2002).

As mentioned the memory for familiar environmental spaces typically is orientation-independent (e.g., Evans & Pezdek, 1980; Sholl, 1987; Rossano et al., 1999), whereas orientation-dependency is found in unfamiliar environmental spaces, e.g., learned from virtual reality (Christou & Bülthoff, 1999; Richardson, Montello & Hegarty, 1999; Rossano, et al., 1999). It is known that experiencing multiple views leads to better performance. For children and adults travelling a route in the opposite direction as it was learned benefit from the strategy of looking back more than from retracingor having no specific strategies (Cornell, Heth & Rowat, 1992). Again it is unclear whether the observed orientation-independent performance stems from an orientation-independent representation or from encoding multiple views.

2.4.1.3 Summary

To summarise spatial knowledge of familiar spaces is orientation-independent when experiencing it in multiple directions. This is the case, for figural, vista, and environmental spaces. As maps are usually experienced only in one direction, map knowledge is orientation-dependent. The debate between whether orientation-free performance stems from orientation-free memory or from storing multiple views and interpolating between them has not been solved. Familiarity was discussed in the context of view-dependency. Familiarity was also seen as a crucial issue for the development of landmark, route and survey knowledge.

2.4.2 Landmark, route and survey knowledge

Piaget and Inhelder (1967) distinguished knowledge about environmental spaces in landmark, route and survey knowledge. Many other authors referred to this distinction and especially distinguish between route and survey knowledge (e.g. Golledge, 1999; Herrmann, Schweizer, Janzen & Katz, 1998; Montello, Waller, Hegarty & Richardson, 2004; Siegel & White, 1975). Landmark knowledge refers to recognising individual landmarks without knowing about the spatial relations between them. Route knowledge tells you where to go when you are at a location independent from knowing the exact position of your goal, e.g. turn right at the church, then the second street to the left. It is “string-like” and usually measured by errors in a wayfinding task. Survey knowledge on the other hand tells you in which direction and distance a location is to be found independent from knowing a path which leads you there, e.g. the train station is about 300 meters east from here. It is the knowledge of the layout of locations and their spatial interrelationships. It is “map-like” and usually measured in shortcut behaviour, in a pointing task or in drawing a map.

Different terms are used to express route and survey knowledge (e.g., Taylor & Tversky, 1992). Route and survey perspective are described with different classes of gestures for both English speakers and these who use American Sign Language (Emmorey, Tversky & Taylor, 2000).

2.4.2.1 Developmental sequence

For a long time the acquisition of knowledge was thought of starting with landmark knowledge, progressing via route knowledge, and finally developing into survey knowledge. This was first shown as a sequential ontogenetic development in comparing the knowledge of children of different ages (e.g., Piaget & Inhelder, 1967; Piaget, Inhelder & Szeminska, 1960). Then the developmental claim was extended to the acquisition of knowledge about a specific environment in general (Siegel & White, 1975). There is, however, evidence contradicting a developmental sequence for acquiring knowledge about specific environmental spaces. Survey knowledge can be acquired rather quickly via walking a route twice (e.g. Montello & Pick, 1993) or even watching a slide show of a route only once (Holding & Holding, 1989). On the other hand people very familiar with an area often do not express much survey knowledge at all. For example 75% long term residents of a Latin-American town draw their district in a route like rather than a survey like manner (Appleyard, 1970). Nurses working in a complex hospital up to two years failed to draw maps resembling the hospital. Participants learning this hospital by map and a short guided tour pointed better than the nurses (Moeser, 1988). People also seem to focus on a specific kind of knowledge from start on when learning routes in a driving simulator (Aginsky, Harris, Rensink & Beusmans, 1997). These and similar results speak against a strict developmental sequence from landmark via route to survey knowledge. Instead they can even be regarded as more-or-less independent forms of spatial knowledge (cf. Hanley & Levine, 1983; Montello, 1998).

2.4.2.2 Relation to wayfinding mechanisms

Route and survey knowledge can be seen as the relevant knowledge to apply to processes such as route or metric navigation and strategies such as least number of turns or least angle strategy (cf. 2.3). To apply a least angle strategy, i.e., always choose the route leading as directly towards the goal as possible, one has to know the distance and direction of the goal, which is survey knowledge. To select and navigate a route one has to know at least one possible route leading towards a goal.

Landmark knowledge as its own is not sufficient for wayfinding or reorientation. As one does not know where to go next when only recognising a landmark it does not help for wayfinding. Knowing that one is at a previously encountered landmark does not necessarily mean to also know ones orientation. It is, therefore, not necessarily helpful in reorientation. The only advantage would be to know that one is in an area encountered before. Therefore, spatial knowledge without relations between locations can be widely ignored when dealing with wayfinding and reorientation.

2.4.2.3 Forming discrete knowledge from a continuous input

When looking at route and survey knowledge as (non-metric and metric) relations between specific locations, then one important question arises: How do we form a discrete representation from a continuous perceptual input when navigating around? For acquiring knowledge from secondary sources such as maps or verbal directions, this is no problem as verbal directions refer to discrete entities and in maps specific locations can be extracted by gestalt-laws. Gestalt-laws explain how a sensory input can be structured, e.g., into object and background (e.g., Goldstein, 2002). Gestalt-laws, however, are not sufficient to explain how to extract entities from a dynamically changing inherent concave input experienced during navigation. It is largely unknown how we accomplish this.

One possible solution to the problem of forming discrete parts of knowledge from a continuous input is not solving it at all, but storing spatial knowledge in a continuous form – a cognitive map. This is the hypothesis discussed in the next section.

2.4.3 Cognitive map

2.4.3.1 What is a cognitve map?

The term "cognitive map" was introduced by Tolman (1948) to illustrate the necessity of assuming a memory content other than behaviourist stimulus-response in order to explain spatial behaviour in rats. Since then it has been used as a term for spatial memory in general, but also for describing a specific form of spatial memory (Gallistel, 1990; O'Keefe & Nadel, 1978; Thinus-Blanc, 1987). Although not all of these authors would agree on all points, the specific meaning of cognitive map is associated with the map-in-the-head metaphor referring to a continuous, integrated, metric (mainly Euclidian), two-dimensional representation of space.[6] The cognitive map maps the surrounding environment, so a location in the cognitive map corresponds to a location in surrounding space. Larger distances in the cognitive map correspond to larger distances in surrounding space. A location between two locations in the cognitive map also is located somewhere between the corresponding locations in surrounding space. The

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[6] It might be proposed even more specifically that all elements are equally accessible as a cognitive map is orientation-independent or seen from birds-eye-view without any alignment problems. This idea will not be discussed here.

cognitive map can also represent the surrounding space in a distorted fashion, however, a continuous transition between two locations in the cognitive map corresponds to a maybe distorted, but nevertheless continuous transition in the real world and vice verse.

In the following we would like to argue that such a conception of knowledge is not very useful for representing environmental spaces, as it probably is limited to representing vista spaces and possibly metric representations of environmental spaces in humans.

2.4.3.2 Vista spaces and environmental spaces

As seen in 2.3.1.2 humans and non-human animals can reorient on metric properties such as distances and angles in order to find familiar locations in vista spaces. Hippocampal place cells can be seen to serve as a neural representation for that. A cognitive map is a perfectly plausible knowledge representation suitable to explain these results (e.g., O'Keefe & Nadel, 1978). Without additional assumptions it can, however, not explain why reorientation on geometric cues is more fundamental than reorientation on landmarks (cf. 2.3.1.2).

What is the case for environmental spaces? As we have seen place cells cannot be regarded as representing one *specific* location in an environmental space (cf. 2.3.1.2). People are able to orient in physically impossible virtual environments, e.g., where distant locations are connected via "hyperlinks". Through such a hyperlink one can enter the starting room again after walking straight line through various rooms. Participants can even profit from such hyperlinks (Ruddle, Howes, Payne & Jones, 2000). On the basis of route knowledge such behaviour can be easily explained, i.e., the participants only remember which route takes you where. The locations do not have to be arranged somehow consistently in a two-dimensional (or three-dimensional) space. Such behaviour, however, cannot be explained by assuming only a cognitive map. So the cognitive map claim has to be focused specifically on metric orientation and distinguished from route navigation. It corresponds to survey knowledge not to route knowledge, although correct route knowledge can be derived from it. Other behaviours might be explained by route knowledge, but metric navigation such as shortcutting should be explained by a cognitive map, otherwise the claim of a cognitive map would be superfluous. However, reducing its applicability to metric navigation raises some problems. Empirical results regarding shortcutting and the integration of information from several vista spaces into the cognitive map do not come along easily with a cognitive map. Finally, two theoretical arguments limit its usefulness.[7]

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[7] Note that all conceptions of a cognitive map discussed here refer to knowledge acquired by direct experience. When acquiring knowledge about a town by looking at a map, it might not be

2.4.3.3 No spontaneous integration of separately learned vista spaces into a cognitive map

As mentioned in 2.3.1.2 landmarks learned from two vista spaces, i.e., in an environmental space, are not integrated into a cognitive map compared to those learned from only one vista space. When learning a location within an environment the landmarks had to be visible during learning the goal location. Landmarks occluded while reaching the goal, but visible in other phases of learning were less helpful both in non-human animal studies and in human desktop virtual reality studies (Hamilton, Driscoll & Sutherland, 2002; Sutherland et al., 1987). This argues against a spontaneous integration of landmarks successively visible in two vista spaces into one coherent cognitive map (cf. also Sturz, Bodily & Katz, 2006).

A newly learned room is not automatically integrated within a cognitive map of a familiar campus the room is part of (Wang & Brockmole, 2003). Participants either were instructed to update the campus or to update the room they were located in during rotation. The configurational error, i.e., the relative pointing error, was small for pointing to objects within the room under both conditions. However, it was only small for pointing to locations on the campus when participants were instructed to update the campus and larger when instructed to update the room. If the participants had integrated the room into a coherent representation of the whole environment no difference in the configuration error would have been expected.

2.4.3.4 Shortcutting

Animals can use novel routes to shortcut a route to their goal location. For example, ants can walk straight back to their nest after looking for food on foraging trips. They do so by updating a homing vector (cf. 2.3.1.3). Animals can also approach visible, familiar landmarks from novel directions (cf. 2.3.1.2) and can short-cut a known route in this way. No cognitive map is needed to explain such shortcuts. When representing environmental spaces in a cognitive map, shortcuts should be easily observed while excluding alternative explanations by updating or approaching familiar landmarks. Figure 3 illustrates that: An animal learns a route from A via B to C or learns the routes from B to A and from B to C. The locations A, B and C are stored in a cognitive map. Now the animal should be able to directly shortcut from A to C. The animal should do so without navigating from C via B to A before to exclude updating the position of C. And the animal should do so without any landmark visible from A and C, because the location of C could be inferred when standing at A using this landmark. To the knowledge of

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surprising that this knowledge exhibits map-like characteristics. Then, however, the figural space of the map, not an environmental space is learned.

the author, there is no convincing experimental evidence for any non-human animal to exhibit such a behaviour (see also Bennet, 1996; Wehner, 1999). Some examples will, therefore, be discussed in more detail.

Tolman, Ritchie and Khalish (1946) showed that rats which learned a route to a feeder most often chose the direct shortcut towards the feeder among 18 alternatives when the original route was blocked. However, no cognitive map has to be assumed to explain this behaviour. They might have simply approached the only light source of the room located behind the feeder. In one experiment, bees showed novel shortcuts between two familiar foraging sites (Gould, 1986). This experiment, however, could never be replicated without alternative explanations by prominent landmarks (for a summary see Bennet, 1996; Wehner, 1999).

Landmarks visible from the start and the goal, thus reducing the task to vista space can also serve as explanations for significant shortcut behaviour found in hamsters (Chapuis, Durup & Thinus-Blanc, 1987) and dogs (Charpuis, Thinus-Blanc & Poucet, 1983; Charpuis & Varlet, 1987). When this possibility was ruled out experimentally, hamsters do not consistently choose the direct shortcut more often than other possibilities (Chapuis & Scardigli, 1993).

Non-human animals, hence, do not seem to shortcut in environmental spaces which would be expected when forming a cognitive map. What is the case in humans? Contrary to other animals, humans can shortcut. They do so quite accurately using maps or other navigation tools, but they also do so when learning the environment by direct experience. A two and a half year old blind child was shown to make novel shortcuts between locations in a familiar room (Landau, Spelke & Gleitman, 1984).[8] However, when we shortcut we exhibit rather large errors (Foo et al., 2005): Participants extensively learned a configuration as the one shown in Figure 3. They did so by walking and viewing a desert landscape displayed in an immersive virtual environment. When shortcutting participants missed the target destination by about 50% of the distance between A and C, but they were quite precise when the target could be identified by landmarks. Better performance might be expected when storing locations in a cognitive map.[9]

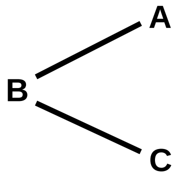

Figure 3: When learning how to get from B to A and from B to C, shortcutting is directly walking from A to C

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[8] The individual locations could only be acquired by walking since vision was not possible and also auditory cues were excluded. Albeit this space, being small in size, could be regarded as an environmental space.

[9] A lack of distance estimation as an alternative explanation is unplausible, as the participants were able to walk precisely towards A and C starting from B.

Why humans seem to differ from non-human animals in their ability to perform shortcuts will be discussed in 4.2.2. However, the rather bad shortcutting performance in humans and the lack of evidence for shortcutting in animals do not support the claim of a cognitive map in general and especially for animals.

2.4.3.5 Multiple cognitive maps are necessary

Aside shortcutting and integration of vista spaces into one coherent cognitive map also two theoretical arguments limit the applicability of the concept of a cognitive map. Both speak against the claim of a continuous, integrated representation of space.

When using knowledge for any task such as reorientation or wayfinding the relevant knowledge has to be active in working memory (cf. Anderson, 1995). However, working memory is limited (e.g., Baddeley, 2003). A cognitive map is a continuous representation of space. In order to use a cognitive map it has to be represented entirely in working memory – at least the area used for orientation. So the cognitive maps could not be too large. It is questionable whether a whole town could be represented in that way.

A cognitive map is an efficient way to represent metric spatial representations. To list pair wise distances between towns can result in a very long list. Representing the locations of these towns in a map is, however, computationally rather easy, as we all know from paper maps. Here we easily can extract the distances between two towns. Unfortunately as a distance has to be computed this works only well for maps up to a certain size.

The second argument points out that we always have to use multiple cognitive maps anyway. We surely do not have one and the same cognitive map to represent our hometown, New York and Paris. When exploring an unfamiliar city, e.g., by subway, we learn several areas of this town around the subway stations. It is hard to imagine, that these areas are at least at first represented in the same cognitive map. Otherwise this cognitive map would often need rebuilding when walking from one subway station to another, encountering familiar areas.

Both arguments point out that cognitive maps as continuous integrated representations of space cannot be too large. We have to have multiple cognitive maps representing our environments. If that is the case, the spatial relations between these maps have to be somehow stored. This is against the original idea of a cognitive map as a continuous integrated representation of space.

In a more general form this is the question of what are the parts of knowledge we represent in our environment? Here a general trade-off exist between the size of the parts, i.e., the spatial area they cover, and the number of parts. The smaller the parts, the more parts, and especially relations between the parts have to be encoded in order to represent a certain space in mind. Representing each cobblestone of a street as an individual spatial part would result in a lot of relations. Integrating everything within one large representation is inconsistent with a limited working memory and learning an environment part by part. There is probably a computational optimum regarding the size of the parts. As limitations, a lot of unknown parameters play a role here, e.g., how many details we encode of an environment? What are the exact limitations of our working memory for spatial content? It is hence not yet possible to determine such an optimum. As a first guess one might feel inclined to regard vista spaces as the size of such parts. This question will be discussed further on in 4.2.2).

2.4.3.6 Summary

The term cognitive map was used for spatial knowledge in general, and more specifically for a conception of spatial knowledge associated with a map-in-the-head metaphor, where space is represented in a continuous, integrated, metric and two dimensional way. This conception is appropriate for explaining most empirical results concerning single vista spaces. For environmental spaces, however, cognitive maps cannot explain the orientation in impossible environments, the problems of integrating multiple vista spaces and the failure of non-human animals to find novel shortcuts based solely on a cognitive map, respectively the problems humans have in doing so. Theoretical arguments show our knowledge has to consist of multiple units. Taken together it does not seem very useful to understand spatial knowledge of environmental spaces as continuous, integrated, and metric as would be the case with cognitive maps.

2.4.4 Biases in spatial knowledge

Our spatial knowledge is not just a more or less precise representation of space where only random errors occur and these errors decrease when becoming more familiar with an environment. Our knowledge is systematically distorted. These distortions are consistent over different environments and are encountered in figural, vista, and environmental spaces. First, we will consider distortions considering edges such as streets or coast lines. Second, we will consider biases due to regionalising spaces. Third, we will consider biases in distance and location estimation due to connectedness and available landmarks.

2.4.4.1 Straightening edges, aligning edges and squaring oblique intersections

When remembering urban environments, e.g., by drawing a map, edges such as streets or rivers are usually remembered as *straighter* than they are (e.g., Byrne, 1979; Milgram, 1976). Biases in direction estimations in unfamiliar figural spaces and in familiar geographic spaces which typically are learned from maps can also be interpreted in straightening an edge, such as the border between Canada and USA (Stevens & Coupe, 1978).

In maps of familiar urban environments (Byrne, 1979; Lynch, 1960; Milgram, 1976; Tversky, 1981) and newly learned virtual environments (Gillner & Mallot, 1998) intersections are distorted towards *right angles*. Even angles of 60° or 120° are often drawn as being orthogonal (Gillner & Mallot, 1998; Tversky, 1981). Under laboratory conditions, angles walked while being blindfolded are recalled as being more like right angles (e.g., Sadalla & Montello, 1989).

When comparing performance in different environmental spaces oblique intersections pose specific problems. Pointing in real (Montello, 1991; Thorndyke & Hayes-Roth, 1982) and virtual environments (Werner & Schindler, 2004), distance estimation in buildings (Thorndyke & Hayes-Roth, 1982) and navigating to objects in a desktop virtual environment (Ruddle & Peruch, 2004; Werner & Schindler, 2004) is more difficult, when oblique angles occur than when only orthogonal angles are encountered. One possible explanation for problems with such oblique intersections is remembering the oblique intersections as more orthogonal.

In maps of familiar urban environments streets are often drawn *aligned* with each other and with reference directions such as north. This was found in map drawings (Byrne, 1979; Tversky, 1981) and in maps derived from distance estimations (Lloyd & Heivly, 1987). Alignment effects do not only occur in memory for urban environments, but also in memory for figural spaces learned from real and fictious maps. The orientation of islands and continents on world maps and on fictious maps is distorted towards the north-south respectively the east-west line, which is also the orientation these maps are usually displayed. This was shown in direction estimation, map drawing, and map recognition tasks (Tversky, 1981). Inferred from direction judgments, coastal lines such as in California or Israel are tilted inacurately towards upright (Glickson, 1994; Portugali & Omer, 2003; Stevens & Coupe, 1978). Interestingly, direction judgements along the coast line and between rather close cities are not distorted (Portugali & Omer, 2003).

Some of the straightening and alignment effects reported here have been interpreted as being caused by storing knowledge about geographic spaces in a hierarchical form (Friedman, Brown & McGaffey, 2002; Stevens & Coupe, 1978). Although this is a valid interpretation for many reported results, the explanation is less plausible for alignment effects without salient geographic regions (Portugali & Omer, 2003).

2.4.4.2 Biases due to regionalising spaces

Results from Stevens and Coupe (1978) reported in the last section have been interpreted by the authors themselves as evidence for hierarchical clustering of spatial knowledge (San Diego is in California, Reno in Nevada). As California is west of Nevada, participants estimate also San Diego as lying further to the west than Reno, even it is the other way round. This explanation is also valid for many alignment effects found in real and fictious maps (Stevens & Coupe, 1978). Similar effects due to building regions in maps and other figural spaces have been observed.[10] Distances are estimated shorter when being within a political region (e.g., Carbon & Leder, 2005). The clustering of cities to regions can be derived from direction and distance estimations (Friedman & Brown, 2000; Friedman & Montello, 2006). Latitude and longitude estimates can be influenced by facts given during the experiment (Frieman & Brown, 2000); distance estimations can depend on attitudes towards inhabitants of a region (Carbon & Leder, 2005). These results indicate that geographic judgements are not based on stable spatial representations. Regions in fictious maps can be built from given semantic labels as is shown in placing, distance estimation and relative distance judgement tasks (Hirtle & Mascolo, 1986). Judgements made on across-region pairs of real and artificial cities are faster and not influenced by distance compared to a pair within a region (Maki, 1981; Wilton, 1979). Objects of a previously learned layout prime objects on the same region more strongly than objects from other regions (McNamara, 1986; McNamara, Hardy, & Hirtle, 1989).

Regionalisation effects are not only found in memory, but also in perception. In such experiments estimations are made while watching the stimulus. Direction judgements are verified faster for objects of two groups defined by colour or shape than for two objects of the same group (Hommel, Gehrke & Knuf, 2000). Distances between two points are estimated shorter when both points are part of a figure defined by Gestalt laws than when just one point is part of the figure (Coren & Girgus, 1980).

Regionalisation effects are also found in object arrays presented in vista spaces as is shown in priming, direction and distance estimation. The regions were induced by strings on the floor of a room (McNamara, 1986) or each participant spontanously clustered the objects into regions. These subjective regions were determined in a recall task and predicted performance (McNamara, Hardy & Hirtle, 1989). In environmental spaces distances are estimated and drawn as shorter when lying within an individually determined semantic region of a familiar university campus (Hirtle & Jonides, 1985) or within a region defined by landscape and learned from a walk presented on photo slides (Allen, 1981).

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[10] The spatial relations between real cities can be learned by direct experience and from maps. However, as navigation between cities usually is not done on foot we assume that map learning is the more relevant source of information.

Route decisions are also influenced by regions. Participants prefer routes that cross fewer regions to routes that cross more regions. This is found in route choices made on given maps (Bailson, Shum & Uttal, 2000), and in route choices based on memory of virtual environmental spaces (Wiener & Mallot, 2003). In such virtual environments participants approach the goal region directly although other routes of equal length are available.

2.4.4.3 Biases due to connectedness and available landmarks

Distances in figural spaces are estimated shorter and locations prime each other more strongly when the locations are connected with a line than when they are unconnected (McNamara, Ratcliff & McKoon, 1984). This effect is probably due to perceptual organisation as biases in distance estimation are found even when spatial judgements are made by using a permanently visible map (Klippel, Knuf, Hommel & Freksa, 2005).

Memory for a location presented on a computer screen or in a circle printed on a rectangular sheet of paper is distorted towards the centres of four quadrants (Huttenlocher, Hedges, Corrigan & Crawford, 2004; Huttenlocher, Hedges & Duncan, 1991; Gourtzelidis, Smyrnis, Evdokimidis, & Balogh, 2001). Similar categorisations with only two categories were found for memory of dots within rectangles (Huttenlocher, Newcombe & Sandberg, 1994), or within a v-shaped figure (Engebretson & Huttenlocher, 1996).

'Landmarks', e.g., dots on a computer screen, influence the memory for locations. In general locations are remembered as lying closer towards the landmark (Diedrichsen, Werner, Schmidt & Trommershäuser, 2004; Hubbard & Ruppel, 2000; Nelson & Chaiklin, 1980) except for the region immediately surrounding the landmark (Schmidt, Werner & Dietrichsen, 2003; but see Gourtzelidis et al., 2001). Also in vista spaces locations are remembered as lying closer to visible landmarks (Fitting, Allen & Wedell, in press).

The effects of categorisation of locations and distortions towards landmarks have been explained by averaging location information provided by the prototype of a category memory and a fine-grained coordinate memory (e.g. Huttenlocher et al., 1991).

2.4.4.4 Summary

Our spatial memory is biased in various ways. First, recalled edges are straightened and aligned with each other and with reference directions. Second, angles are recalled as more orthogonal. Third, especially for figural spaces, but also for vista and environmental spaces, knowledge is organised in regions. These regions can origin from perceptual grouping of locations, from visible borders between locations, from available frames such as computer screens or from semantic grouping in general which could encompass political or conceptual similarities. Many of the effects described can by interpreted in various ways. However, most of the effects can be explained by encoding spatial information not only in a fine-grained spatial way, but also in a categorical way with both systems contributing to judgements about spatial relations (e.g., Huttenlocher et al., 1991; Kosslyn et al., 1989).

2.4.5 Frames of reference

A reference frame is a means of representing the location of entities in space (Klatzky, 1998). It is a conceptual basis for determining spatial relations (Miller & Allen, 2001). The entities within a frame of reference can be objects such as chairs or churches, but they can also be located features, e.g., the corner of a room, a crack in the chair, a splotch in a paining or the dot of the letter i (cf. Campbell, 1993; Herskovits, 1986). Frames of reference most often are understood as coordinate systems. For example for visual perception retinal, head centred, and body centred reference frames are used (e.g. Pinker, 1984). Head centred coordinates express locations adjusted for gaze movements, whereas body centred coordinates express locations adjusted for head movements. In linguistics, intrinsic, relative, and absolute reference frames are used (e.g., Levinson, 1996; 2003; Majid, Bowerman, Kita, Haun & Levinson, 2004). For the purposes here, the most important distinction is between egocentric and allocentric reference frames.

2.4.5.1 The existence of egocentric and allocentric reference frames

Definition. In the literature on spatial representations it is common to distinguish between egocentric and allocentric frames of reference (e.g., Burgess, 2006; Klatzky, 1998; McNamara & Valiquette, 2004; Sholl & Nolin, 1997; Wang & Spelke, 2002). In an egocentric reference frame object-to-self relations or more general location-to-self relations are represented, e.g., the ball is in front of me. More specifically these egocentric representations can be described in a polar coordinate system with the body as origin and the front of the body as the reference direction (Klatzky, 1998). A location in an egocentric reference frame is defined by the direction and distance to one's position.

In an allocentric reference frame object-to-object relations or more general location-to-location relations are represented, e.g., the church is north of the city hall. Allocentric representations can be described in a polar or Cartesian coordinate system. The axis of the coordinate system might be given in advance, e.g., north or gravitational upright. It might be defined by the learning experience e.g. the first view encountering a space. Or it might be defined by the 'intrinsic' layout of the space itself, i.e., its natural orientation such as the front direction of a car or the long axis of a rectangular room, a rectangular array of objects or a rectangular sheet of paper (e.g., O'Keefe, 1991; McNamara & Valiquette, 2004). Some conceptions of allocentric reference frames do not assume an explicit axis (e.g., Sholl, 2001; Sholl & Nolin, 1997). These conceptions only focus on location-to-location relations. As the examples show, such an allocentric reference frame can be defined for all forms of spaces relevant here: figural, vista and environmental space.[11]

A location can be represented in an egocentric reference frame, i.e., with respect to ones current position (location and heading), or a location can be represented in an allocentric reference frame, i.e., with respect to other locations in the space. Any location represented in an egocentric reference frame can also be represented in an allocentric reference frame and vice versa. Every spatial relation e.g., the bearing between two objects as seen from a third object which can be computed in an egocentric reference frame can also be computed in an allocentric reference frame and vice versa. Both representations are, therefore, mathematically equivalent. However, some relations are rather directly represented in one reference frame, e.g. the direction of an object with respect to ones position in an egocentric reference frame. From an allocentric reference frame this direction would have to be derived.

An important consequence of this definition of the egocentric reference frame is that the egocentric representation changes, as we move around. The locations of the objects surrounding us have to be updated either by vision and/or by inertial cues (cf. 2.3.1.3). Contrary to this, allocentric representations do not change as we move around. Only our own position has to be updated with respect to the allocentric reference frame. This definition of egocentric following Klatzky (1998) is different from other conceptions (e.g., Burgess, 2006; Sholl & Nolin, 1997; McNamara & Valiquette, 2004; Wang & Spelke, 2002). In addition to the mentioned conception of an egocentric reference frame which is updated during movement, these other conceptions also assume an enduring egocentric representation, e.g., views stored in long-term memory. In our conception such views are allocentric representations as they store locations in relation to a point of view they were experienced at a specific point in time. This location of the point of view does not change while moving further on. We will first consider evidence for egocentric and allocentric representations as defined here and then will look at different conceptions of allocentric reference frames, e.g., as defined by the experienced view.

Evidence for an egocentric reference frame. The question whether we encode a space in an egocentric or an allocentric fashion has been intensely debated over the last couple of years (e.g., Burgess, 2006; Holmes & Sholl, 2005; McNamara & Valiquette, 2004; Wang & Spelke, 2002). As evidence for an egocentric frame of

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[11] A geographic space is learned from figural spaces.

reference we want to provide results concerning neglect, updating, and disorientation.

Studies from patients with *neglect* show that they specifically ignore or neglect one side of their egocentric reference frame when exploring a space visually or haptically (Konczak, Himmelbach, Perenin & Karnath, 1999; Niermeier & Karnath, 2000). Also imagining familiar vista spaces is impaired in an egocentric fashion (e.g., Bisiach & Luzatti, 1978). Asked to imagine a highly familiar city square while facing east, such a patient may report only the buildings to the south; asked then to imagine the same square while facing west, the patient will report only the buildings to the north. These effects are very difficult to explain assuming only an allocentric frame of reference.

As described in 2.3.1.3 we are able to keep track or *update* the locations in space while moving around. This directly means representing locations in an egocentric frame of reference. For example recognising changes in a layout of objects on a table is easier when we move around the table updating our current view of the layout than when the table is moved and we cannot update the view (e.g., Simons & Wang, 1998; Wang & Simons, 1999). An allocentric encoding of the object layout would not predict such an advantage for updating without further assumptions.

Evidence for an egocentric representation also comes from the *disorientation effect*. When located in a room with several objects disorientation impairs relative direction judgements between objects (Waller & Hodgeson, 2006; Wang & Spelke, 2000). An allocentric coding would predict, that the objects are encoded with relation to each other, i.e., a layout of objects is encoded. So when disoriented, one's position with respect to the whole layout should deteriorate, but less so the relative direction judgements between the objects. This is not the case. When only the relative direction of each object with respect to oneself is encoded, i.e., an egocentric reference frame is used, no relative object directions would be preserved during disorientation.

Evidence for an allocentric reference frame. There is evidence for an egocentric reference frame. However, there is also evidence for an allocentric reference frame. This evidence is also found in updating and disorientation as well as in hippocampal place cells and the development of language.

Despite *updating* a learned array of objects by path integration and vision, pointing to other objects with closed eyes is better when oriented on the orientation the array was learned originally than when misaligned to that orientation by 225° (e.g., Mou, McNamara, Valiquette & Rump, 2004). When representing the objects in an egocentric reference frame only, no drop in performance would be expected.

When all locations are stored in an egocentric reference frame and updated during movement, performance should decrease with the number of updated relations. Such a decrease is found for one to three objects presented only for several seconds (Wang et al., 2006). However, for longer presentation times no such decrease in pointing accuracy can be found between arrays of 4 and 15 objects learned before (Hodgson & Waller, 2006). Indeed, room geometries and a familiar campus can also be updated (cf. 2.3.1.3; e.g., Holmes & Sholl, 2005; Wang & Spelke, 2000). This should pose problems when every location is represented individually in an egocentric reference frame. If, however, the object arrays, the shape of the room or the familiar campus is represented in an allocentric reference frame the whole configuration could be updated instead of updating each location individually. This would explain why performance does not decrease with the number of relations to be updated. An allocentric reference frame has to be assumed to do so. Assuming an allocentric reference frame is also plausible for representing objects such as a bottle with located features as the top, the centre and the bottom of a bottle. When representing these feature locations in an egocentric fashion, the spatial relations between top, centre, and bottom should suffer from random error during updating. However, no matter how long one walks around, the bottle as a whole is normally recalled rather well. This would not be expected when storing located features egocentrically, but is very plausible when storing the features relative to each other, i.e., in an allocentric way. The same argument holds true for very distant locations. With only an egocentric reference frame as defined here we would have to update the location of our home town during holidays in Kenya, which is very implausible.

As mentioned *disorientation* deteriorates relative direction judgements between objects (Waller & Hodgeson, 2006; Wang & Spelke, 2000), but not so the relative direction judgements between the corners of a room (Wang & Spelke, 2000). So participants can store the configuration between locations like corners which means they use an allocentric reference frame. Otherwise the relative direction judgements between the corners of a room should deteriorate, too, like the ones between objects. With longer learning time for objects in an earlier phase of the experiment, an allocentric array of objects can be encoded. As a consequence relative direction judgements between objects are not affected by disorientation any more (Holmes & Sholl, 2005). Even more generally, reorientation can only be done on allocentric representations, as disorientation deteriorates egocentric representations and no available representation to orient onself would be available.

Further evidence for the existence of an allocentric reference frame comes from hippocampal *place cells* in rats and humans (see 2.3.1.2). These cells represent the location with respect to an allocentric reference frame defined by the surrounding vista space.

The last evidence for an allocentric reference frame comes from the *development of language*. Expressions corresponding to an egocentric frame of reference, e.g., 'left of' (in this context called relative reference frame) are learned later than allocentric expressions such as 'in front of the car', with respect to the car (intrinsic reference frame), or 'north of' (absolute reference frame) (Levinson, 1996). If there was only an egocentric reference frame, expressions directly linked with it should be easier to learn.

Conclusions. Many experiments concerning egocentric and allocentric reference frames have been conducted. Except for updating environmental spaces all mentioned experiments took place in vista spaces. Both egocentric and allocentric representations have to be assumed to explain the mentioned effects (in a sufficiently simple way). Many theoretic positions assume both kinds of representations (Burgess, 2006; Holmes & Sholl, 2005; McNamara & Valiquette, 2004). It seems likely that many aspects of the spatial representation we have in a specific moment are best described in an egocentric way with the elements such as the shape of the room, or the objects represented in an allocentric fashion. Due to our definition, the egocentric reference frame is transient and updated online during movement. However, all content of long-term memory is hardly dependent on our current position. Spatial long-term memory should, therefore, be considered as allocentric. As the construction of the world surrounding us from our senses also depends heavily on long-term memory content, this current world representation shows many, but not exclusively allocentric aspects. In the next section we want to discuss allocentric reference frames in more detail.

2.4.5.2 The nature of allocentric reference frames

We argued that spatial long-term memory content is always allocentric, i.e., location to location information is stored. Obviously this is also true for external spatial representations such as maps. There are, however, different conceptions of allocentric reference frames. The main consequences from these conceptions are different predictions concerning transformation costs. Transformation costs occus when transforming spatial information from one reference frame to another, e.g. transforming allocentric memory or an external map towards an egocentric reference frame in order to perform tasks such as pointing. We will first, introduce different conceptions of allocentric reference frames and then look at empirical results concerning figural, vista and environmental spaces.

Theories of allocentric reference frames. Several theories of long term memory for vista and environmental spaces have been proposed (e.g., Mallot & Gillner, 2000; O'Keefe, 1991; Sholl, 2001; McNamara & Valiquette, 2004; Wang & Spelke, 2002). We want to distinguish these theories regarding their orientation specificity. More specifically these theories either assume that we store spatial information in an orientation independent manner, we store them orientation-dependent with respect to a reference direction or we store them orientation-dependent with respect to an experienced direction. These three theoretical positions will be explained in more detail.

Memory is orientation independent. An orientation independent representation has mainly been argued for by Sholl and her colleagues (e.g., Easton & Sholl, 1995;

Holmes & Sholl, 2005; Sholl, 2001; Sholl & Nolin, 1997). The main allocentric component of their theory is organised in vectors connecting spatially close objects. Inter-object distance is represented by vector magnitude. Relative direction is represented by angles between vectors emanating from a common origin, i.e., object. Spatial relations are specified with respect to other objects. Relative direction is preserved locally among a set of objects, but not with respect to the whole environment. There is no reference axis.[12] No performance cost is, therefore, expected for not being aligned with a reference direction or an experienced view.

In addition to this orientation-independent system, Sholl and colleagues assume also an egocentric reference system. Newer versions even assume an allocentric view-dependent system.[13] These egocentric and view-dependent systems mainly apply for ealier stages of learning. For well learned environments performance is determined by the orientation independent system.

Memory is orientation-dependent on a reference direction. Reference direction theory assumes that objects are encoded with respect to one or two reference directions which function like coordinate axes, e.g., "north" (e.g., Mou, McNamara, Valiquette & Rump, 2004; McNamara & Valiquette, 2004). Retrieving information from memory works best when being oriented along a reference direction. The memory, therefore, is orientation-dependent with respect to a reference direction. Such a reference direction originates either from the initial contact with an environment, e.g., the first view of a room after entering it, or it is changed to the main or 'intrinsic' orientation of an environment. For example a reference axis is aligned with the walls of a room rather than oblique to that orientation. Such intrinsic reference axes could be derived performing a principal component analysis with all locations of an environment (O'Keefe, 1991). The mass centre of such an environment could serve as the origin of a coordinate system. Such an origin, however, has no functional role in reference theory.

Memory is orientation-dependent on the experienced view. A last class of theories, the view dependent theories, assume the environment is stored in the local orientation it was experienced (e.g., Christou & Bülthoff, 1999; Mallot & Gillner, 2000; Wang & Spelke, 2002). Performance is better when facing or imagining the experienced orientation than when facing another direction. Each view corresponds to a single reference frame. Many authors call this kind of representation egocentric (e.g., Burgess, 2006; Holmes & Sholl, 2005, McNamara & Valiquette, 2004; Wang & Spelke, 2002). As mentioned before we define egocentric as relative to ones *current*

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[12] This theory could be described as having many local reference frames. Two objects can be seen as defining a reference frame, such as a polar coordinate system. The location of a third object is defined within this reference frame. However, an equivaled view would be that the second and the third object define a reference frame within which the first object is located.

[13] This allocentric view dependent system is called egocentric by the authors. We, however, stick to the terminology used here (see also view depedent theories).

position (Klatzky, 1998). Storing a view in this context means storing locations with respect to a location in space, i.e., the viewpoint from which the environment was experienced at a certain point in time. That, in our definition is an allocentric representation. Viewpoint-dependent encoding also does not mean that every location, every located feature, is exclusively encoded in relation to the viewpoint. As seen in the last section object features probably are encoded in relation to each other and the whole object can be encoded in relation to the viewpoint. Similary, the corners of a room probably are encoded in relation to each other and the whole room geometry can be encoded in relation to the viewpoint.

Distinguishing between the theories. In order to distinguish between these different theories, transformation, especially alignment, costs are considered. When an environment is encoded with respect to a reference axis and when being not aligned with the reference axis, recognition or pointing performance should decrease. The process of aligning with the reference frame, e.g., by shifting ones perspective, is an extra process not necessary when aligned with the reference axis. This extra process costs performance with respect to accuracy and/or time. For view dependent theories, the reference frame is the experienced view. Orientation independent theories do not predict any transformation costs for well learned environments. For all this, updating has to be excluded as an alternative explanation. In the next sections we will discuss specific experimental results concerning the different approaches when orienting in vista and environmental spaces.

Vista spaces. As seen in 2.4.1 when vista spaces are learned from only one or few perspectives performance usually is better when oriented along these perspectives (e.g., Diwadkar & McNamara, 1997; Iachini & Logie 2003; Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997; Walleret al., 2002). Contrary to these results several experiments have shown that the layout of an array of objects and/or the geometry of a room might also serve as a reference axis. When imagining being aligned with such a reference axis pointing performance can be better than when imagining being aligned with an experienced view (Mou & McNamara, 2002; Shelton & McNamara, 2001; Valiquette & McNamara, in press).For example participants learned an object array in a rectangular room from several different viewpoints. Either first from a view oblique to the room geometry and then from a view aligned with the room geometry, or they learned the array first from a view aligned with the room geometry and then from a view oblique to that. No matter in what order they learned the array the participants performed best in a pointing task when imagining the view aligned with the geometry (Shelton & McNamara, 2001; Valiquette & McNamara, in press). Learning a layout from another perspective than the current one works better when the to-be-learned-perspective is aligned with the room than when oblique to it (Mou & McNamara, 2002). These results cannot be explained by the experienced views only. The results indicate the existence of a reference direction which is aligned with the geometry of the room that the object array was located in. These effects, however, can also be interpreted in another way. For the imagined pointing tasks used in these experiments the participants were located in another room. Assuming the participants were aligned with the geometry of this other room while imagining standing in the room they learned the object array. It should be easier for the participants to imagine being also aligned with the room walls than when imagining standing oblique to the room walls. This would be predicted by interference theory (May 1996; 2004; see also 2.3.1.3) where interference between the actual and the imagined orientations is greater when the actual and the imagined room geometry differ.[14] Interference would also explain the better performance in all four imagined orientations aligned with the wall geometry compared to imagined views oblique to the walls often found in these experiments. This effect was explained by assuming additional reference axes. The advantage in alignment with the room geometry also vanishes when a recognition task is used instead of an imagined pointing task. In that case performance is best for the experienced views not the assumed reference axes (Valiquette & McNamara, in press).

No matter whether the effects are from interference during imagined pointing or from a reference axis imposed by the room layout, they point out the importance of room geometry as a salient cue in relation to which the objects in a room are encoded. This is consistent with results from reorientation (see also 1.3.1.2). However, the effect of the experienced views is quite strong and cannot be ignored. So the situation might be similar to object recognition and both viewpoint dependency and structural components probably play a role (cf., Hayward, 2003).

All experiments mentioned in this section showed alignment effects which are not predicted by orientation-independent theory. As all layouts were learned during the experiment, learning time might not have been sufficient to form an orientation-independent representation. Also a theoretical argument speaks against the mentioned form of orientation-independent theory. Equal performance for all orientations could be explained by storing multiple views only. The proponents of orientation-independent theory assume a view dependent representation system additional to an orientation-independet one anyway. From a mere theoretical point of view storing multiple views in the view-dependent system is sufficient to explain the lack of orientation effects. Assuming an orientation-independent system additional to a view-dependent one is superfluous as it does not explain more than could be explained by the view-dependent system alone. This argumentation also applies for environmental

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[14] In Experiment 3 of Mou and McNamara (2002) the layout was learned in a circular room excluding interference between room geometries as an explanation. The effects were smaller, however, still significant. When explicitly instructed to do so, it is, therefore, possible to encode an object array organised in horizontal and vertical lines in that orientation, even when it is seen from a different angle.

spaces. The orientation-independent approach is therefore not further discussed for environmental spaces.

Environmental spaces. Similar for the situation in vista space, view dependent theory predicts storing various views. Reference direction theory predicts the storage of locations within one global frame of reference, e.g., with respect to cardinal directions at any point in the environment. Orientation-independent theory predicts no performance advantages for being aligned with experienced views or with reference directions. To the knowledge of the authors no experiments directly compared these different claims for environmental spaces.[15] Indirect evidence can, however, be drawn from global orientation cues, from frames of reference used in language and from switching costs within an environment.

When learning virtual environmental spaces displayed on large screens, participants profit from cues providing global orientation such as distal landmarks (Steck & Mallot, 2000) or uniform slant (Restat et al., 2004). If environmental spaces where always stored correctly with respect to a global reference direction no advantage for additional compass information would be expected. In the mentioned experiments, however, no inertial cues for updating ones orientation in space were available. Due to that, participants might have stored locations incorrectly, but nevertheless in relation to a global reference orientation. Generally, people who report keeping track of their global orientation when moving around, perform better in spatial orientation tasks (e.g., Hegarty, Richardson, Montello, Lovelace & Subbiah, 2002).

Many language communities make extensive use of global orientation information such as ‘north’ (also called absolute reference frame) (Levinson, 1996). These communities would not say “the child was standing left of the tree”, but would report “the child was standing west of the tree”. In order to do so accurately the speakers must be constantly and correctly oriented to the global orientations. This could indicate that at least in some cultures such locations are stored with respect to a reference direction. However, such (absolute) reference frames used in language do not have to refer to north, south, west, east. On islands also a mountain-sea axis can be used which rotates as one moves around the island. Many language systems abstract the used reference frame from local landmark features such as a mountain incline, but use it also outside of the territory. Rivers are used for a reference frame which changes when crossing into another drainage system. Such reference frames might, therefore, differ between environments. So

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[15] As mentioned before in the experiment of McNamara, Rump and Werner (2003) participants pointed to locations on a large open field with a rectangular temple in the middle defining a frame of reference. As many locations could be seen from others locations, this environment can be understood as a vista space rather than an environmental space. Additionally, participants in this experiment were able to look around. The experienced views were not strictly controlled.

even cultures extensively using global orientation information in their languages do not always refer to one or more constant reference directions used for larger areas.

There is evidence against the existence of one global reference frame within a familiar university building. Although keeping the same imagined global orientation within the building, switching between two imagined locations for a verification task decreases performance compared to staying in the same location (Brockmole & Wang, 2002). Switching the imagined orientation decreases performance more strongly when staying in one location than when additionally changing the imagined location (Brockmole & Wang, 2003). When there was one reference direction underlying the whole environmental space, switching costs due to orientation should be equal in the whole space.

Taking the sparse evidence together, people are able to profit from global reference information to orient themselves. Some cultures and some individuals do so extensively and doing so is probably associated with good orientation performance. Within a language community global reference information is not restricted to one or more cardinal directions and can change between different environmental spaces. Further research has to clarify whether this reference information is a fundamental reference frame underlying spatial knowledge of an environmental space or this reference information is an additional cue used to organise smaller parts of spatial knowledge with individual reference frames (cf. Poucet, 1993).

Figural spaces used for orientation. As mentioned before the perspective in which a figural space is encountered plays an important role. Generally objects are recognised better when encountered in the experienced orientation (e.g., Bülthoff & Edelmann, 1992; Tarr, 1995). However, structural elements are also relevant for recognition (cf. Hayward, 2003). Also maps are figural spaces and they seem to be encoded in the orientation experienced, e.g., north-up (see 2.4.1; e.g., Evans & Pezdek, 1980). For orientation, however, recalling a map is not the only part. In order to use the map, its information has to be transformed from the reference frame of the map to the reference frame used for interacting with vista and environmental spaces. This applies for maps recalled from internal memory as well as for using the external representation paper map. The transformation consists, first, in aligning both reference frames. 'Up' in the map must correspond to 'forward' in the environment. Second, the transformation also consists of shifting perspective from the birds-eye-view of the map to the horizontal perspective in which we encounter vista spaces. These processes will be described in more detail.

Wayfinding with 'you-are-here-maps' is better when a map is aligned with the surrounding environment, i.e., 'up' corresponds to 'forward' than when they are oriented in another way. This was found using you-are-here-maps in a real building (Levine, Jankovic & Palij, 1982) as well as in learning a path in vista space from a map and navigating it afterwards in a desktop virtual environment (May, Peruch & Savoyant, 1995). Similar results were obtained in walking to locations in vista space identified on a map (Warren, Scott & Medley, 1992). Pointing performance is better when aligned with a map of a simple vista space (e.g., Presson & Hazelrigg, 1984; Presson, DeLange & Hazelrigg, 1989; Rossano & Warren, 1989; Tlauka & Nairn, 2004), when aligned with a map of a house learned before (Richardson, Montello & Hegarty, 1999), or when aligned with a map or a model of a campus learned before both for real pointing (Rossano et al., 1999) and imagined pointing (Rossano, Warren & Kenan, 1995). Imagine looking northwards leads to better performance when pointing to large cities whose locations were probably learned from north-up maps (Sholl, 1987; Werner & Schmidt, 1999). Localising ones position on a city map from photographs is easier when the view on the photograph is aligned with the orientation of the map (Warren, 1994).

Aligning 'up' with 'forward' is often described as a process of mental rotation (e.g., Iachini & Logie 2003; Wickens, Vincow & Yeh, 2005). The performance costs such as the time to mentally rotate a figural space generally increase linearly as the rotational angle increases (e.g., Shepard & Metzler, 1971; Cooper & Shepard, 1973). However, two exceptions apply to this rule. First, in stearing tasks, angles between map displays and forward smaller than 45° result in only minor errors (Wickens et al., 2005). Second, mental rotations of 180° are faster than expected by a linear increase, e.g. rotation time increases up to 135°, but then faster times observed at 180° (e.g., Boer, 1991; Gugerty & Brooks, 2001; Hintzman, O'Dell & Arndt, 1981; McNamara, Shelton & Carr, 1998). Participants probably use other strategies rather than mental rotation, e.g., verbal or categorical strategies.

Aligning a map with the surrounding plane is one necessary transformation when using figural spaces for orientation. A second aspect involves the switch of perspectives from birds-eye-view of the map to the horizontal view in which we actually experience vista spaces (e.g., Niall, 1997; Wickens et al., 2005). Such a switch between learning and testing is associated with costs in recognising locations learned from texts and movies (Shelton & McNamara, 2004). Switching within a text between descriptions form birds-eye-view and from horizontal perspective leads to increased reading times (Lee & Tversky, 2001; 2005). Seeing an area from horizontal perspective is associated with different brain activations than seeing this area from birds-eye-view (Mellet et al., 2000; Shelton & Gabrieli, 2002). Interestingly the areas activated when watching the birds-eye-view are part of the areas activated when watching the horizontal view. Intuitively, one might have expected the other way round.[16] The perspective switch probably correponds to something else than mental rotation as described above (Kozhevnikov &

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[16] Effects from perspective switch are also arguments against a simple map-in-the-head metaphor for spatial memory in general.

Hegarty, 2001; Niall, 1997; Wickens et al., 2005). For tasks comparing images from horizontal perspective with ones from birds-eye-view or views in between, substantial costs only appear with angles between views well beyond 45° (Wickens et al., 2005). This might be due to asymmetries in the up-down axis of the body which is not prevalend in the left-right axis (Franklin & Tversky, 1990; Shepard & Hurwitz, 1984).

2.4.5.3 Summary

Reference frames as an underlying concept for the representation of locations in space have been discussed heavily over the past couple of years. Most work has referred to the distinction between egocentric and allocentric reference frames. Following Klatzky (1998) we define an egocentric reference frame as representing locations - not only objects - with respect to ones current position. This reference frame is transient and must be updated during movement. Contrary to that, location-to-location information is represented in an allocentric reference frame. All long term memory is necessarily allocentric. Our current representation of the world contains both egocentric aspects and allocentric aspects such as objects or geometric layouts. Our allocentric representations heavily depend on reference frames originating from the view the space was experienced. This holds true for figural, vista and environmental spaces. However, geometric layout also plays a role in vista space. In environmental spaces global direction information is used as well. An orientation-independent representation of an environment might exist in addition to orientation-dependent ones. However, such an assumption is unnecessary for explaining the mentioned results. When orienting based on knowledge represented in a frame of reference, e.g., in memory or in a map, the knowledge must be transformed to the reference frame specified by the orientation task, e.g., pointing or map drawing. This transformation costs performance. The transformation encompasses aligning the reference frames and, for the case of maps, shifting perspectives between birds-eye-view and a horizontal perspective.

2.4.6 Source of knowledge

We acquire spatial knowledge from various sources such as maps, verbal descriptions, or by walking through a space (cf. Tversky, 1993). As described in previous sections the acquired knowledge often differs according to the source it was acquired from. In this section we will directly focus on these differences.

The most common distinction between sources of knowledge is between direct and indirect experience (e.g., Montello et al., 2004). We directly apprehend a space via sensorimotor experience when we see it or walk through it. Also other sensory inputs can contribute to a direct experience such as auditory information (Loomis, et al., 1998), touch (e.g., Klatzky & Lederman, 2003), or even temperature senses indicating, e.g., wind or sun direction. We will, however, restrict ourselves to vision and inertial cues available during locomotion. Spaces that can be experienced directly encompass figural, vista and environmental spaces.

Apart from directly experiencing a space, we can also learn something about a space from other indirect sources, e.g., verbal descriptions, gestures, pictures, maps or models. These sources represent symbolic spatial relations. For example the verbal instruction"turn left at the church" does not specify an action performed in physical space, but rather a description of this action. From this description we can learn something about the spatial layout even without being there. Also, maps which are figural spaces represent relations in another space typically an environmental space. They can, however, also tell us something about the relations in a vista space, e.g., our seat in a sport stadium, or even another figural space like another map of the same area. The representations can vary by the degree to which they are abstract or iconic, i.e. how much they resemble the space they are representing (cf. Hunt & Waller, 1999). Verbal description are abstract symbols whereas a detailed map or to an even greater extent, a picture taken from an aerial view are iconic representations, Iconic representations resemble the space displayed to a greater extent. In the following discussion we will concentrate on maps and verbal directions, which has been the focus of most research thus far.

A special case that falls inbetween direct and indirect sources of spatial knowledge include virtual environments and maybe also videos. The extent to which they ressemble more direct or more indirect sources must to some extent depend on the setup. We will elaborate on that.

In the following we will discuss what knowledge is acquired from a particular source and how this knowledge differs from the knowledge acquired from other sources. We will consider environmental space, vista space, figural space, in particular maps, verbal directions and virtual environments. In Section 2.5 we will discuss whether such knowledge differences can be explained by different mental representations.

2.4.6.1 Knowledge acquired from environmental space

Spatial knowledge acquired directly from environmental spaces is orientation-dependent unless multiple views of the environment are encountered (see 2.4.1). The knowledge is not continuous and integrated, but is structured in separate units interrelated with each other (see 2.4.3). It comprises route knowledge which allows one to travel from one familiar location to another, but also metric aspects can be represented which allow, for instance, humans to find novel shortcuts (see 2.4.2). Knowledge acquired from environmental spaces does not have to be updated continuously during locomotion. In this sense it is allocentric. People profit from global direction information, however, there is probably no general reference frame underlying all environmental spaces (see 2.4.5.). Knowledge acquired from environmental spaces is systematicly distorted towards right angles and parallel streets. It is probably also hierarchically structured (see 2.4.4).

Knowledge acquired from environmental spaces is assymmetrical for distances between landmarks differing in saliency and for routes travelled. On a familiar university campus participants estimate a distance as shorter when asked the estimate the distance from a salient landmark towards a less salient landmark than when asked to estimate the distance from the less salient landmark towards the salient landmark. Imagining standing at a location and judging a landmark as 'close' is faster for salient landmarks than for non-salient ones (Sadalla, Burroughs, & Staplin, 1980). In familiar cities participants often choose different routes on the way out and back which also indicated asymmetry in spatial knowledge of environmental spaces (Golledge, 1995; Stern & Leiser, 1988).

On a more theoretical level one might wonder what are the important elements of environmental knowledge. Based on interviews Lynch (1960) classified knowledge acquired from a city as a network containing paths (channels where we move along), edges (e.g., roads, sidewalks, walls, seashores), districts (e.g., china town), nodes (e.g., busy intersections or a popular city centre) and landmarks (reference points).

2.4.6.2 Knowledge acquired from vista space

Knowledge acquired from vista spaces is orientation-dependent unless experiencing multiple views of that environment (see 2.4.1). The allocentric reference frame underlying memory for vista spaces is not in all cases identical with the view(s) it was experienced, but can be determined, for example, by a salient geometry (see 2.4.5). The main orientation cues used for reorientation are provided within a single vista space (cf. 2.3.1.2). A continuous, integrated and metric cognitive map can be used to explain orientation performance in a single vista space (see 2.4.3). Memory of vista spaces can be distorted due to clustering or available landmarks (see 2.4.4).

All locations in vista space can be accessed directly. Contrary to that, in order to access an environmental space one has to move around. An environmental space consists of several vista spaces. This is refleced in formal analysis techniques of architectural spaces such as rooms, buildings or cities. Here, originally two different techniques emerged called space syntax and isovist analysis. Space syntax is a set of technologies for the analysis of environmental spaces using simple graphs solely consisting of paths and nodes (e.g., Hillier, 1996; Hillier & Hanson, 1984). One such technique tries to find the longest possible view axes in an environmental space, dividing it into a number of vista spaces each corresponding to one view axis. The number of view axes or vista spaces which can be reached by crossing for example three other vista spaces is called the integration of that vista space. In a city this integration of a vista spaces correlates with the average number of pedestrians or vehicles encountered at that vista space per hour (e.g., Hillier, Penn, Hanson, Grajewski & Xu, 1993; Penn, Hillier, Banister & Xu, 1998). The integration also is associated with route choices of hospital visitors both in unguided exploration and in directed search tasks (Peponis, Zimring & Choi, 1990; Haq & Zimring, 2003). The second technique called isovist analysis is used to describe an individual vista space (e.g., Benedict, 1979). Isovists provide a mathematical framework for capturing local geometrical properties as viewshed polygons. Parameters of an isovist correlate with individual behaviour (e.g., Conroy-Dalton, 2003; Wiener & Franz, 2005). Although, these formal descriptions of vista and environmental spaces were not associated with knowledge directly they indicate different relevant aspects associated with different spaces.

When directly comparing vista and figural spaces it has been shown that 18 to 25 month old children are better able to identify a corner from inside a triangular room, i.e., a vista space, than when standing outside of exactly the same room which would then be considered a figural space (Lourenco & Huttenlocher, 2006).

2.4.6.3 Knowledge acquired from figural space

Knowledge acquired from figural spaces can be used to interact with a figural space again, e.g. recall a location on a monitor or redraw a map seen before. In this case, the figural space is a direct source. When the figural space such as a map is used to learn something about another space it represents, e.g., a city, then the figural space is an indirect source of knowledge about the represented space. Maps can represent vista, environmental and geographic spaces. Contrary to vista and environmental spaces, geographical spaces cannot be experienced directly they are only learned via maps. Geographic spaces are in this sense figural spaces and are, therefore, experienced directly from maps (cf. Montello, 1993).

Knowledge acquired from figural spaces is orientation-dependent unless experienced in multiple views (see 2.4.1). Maps are encoded in an allocentric reference frame with up (north) as a reference direction, probably because they are experienced usually in that orientation (see 2.4.5). Map knowledge can be conceptualised as continuous, integrated and metric (cf 2.4.5). Knowledge acquired from figural spaces such as maps is, however, distorted towards right angles, parallelity and is structured into regions or distorted due to available lines or dots (see 2.4.4).

The formation of knowledge about figural spaces, i.e.the process of encoding objects or understanding maps and other graphical representations, is a whole field of reseach in its own and cannot be covered here (e.g., Goldstein, 2002; MacEachren, 1995; Shah & Miyake, 2005). It should, however, be noted that, like in perception in general not all information from figural spaces is encoded, but it is abstracted and schematised (e.g., Gattis, 2001; Tversky, 2000).

Figural space especially maps often are an indirect source of knowledge. If knowledge acquired from maps is used for wayfinding or reorientation, then transformation processes have to take place resulting in specific errors (see 2.4.5). However, knowledge acquired indirectly via maps can also be compared with knowledge acquired directly by experiencing the environmental or vista space. In knowledge about environmental spaces, route and surevey knowledge are distinguished (see 2.4.2). When comparing the sources, generally more accurate survey knowledge is acquired from maps whereas more accurate route knowledge is acquired from directly experiencing the environmental space (e.g., Lloyd 1989; Moeser, 1988; Richardson, Montello & Hegarty, 1999; Taylor, Naylor & Chechile, 1999; Thorndyke & Hayes-Roth, 1982). The random error in a pointing task based on knowledge acquired directly from environmental spaces differs due to the location, which is not the case for knowledge acquired from a map (Giraudo & Pailhous, 1994). Also the orientation specificity is different for knowledge acquired from a map than acquired directly from the corresponding environmental space (e.g., Richardson, Montello & Hegarty, 1999; Rossano et al., 1999).

Further indication for distinguishing between knowledge acquired from environmental spaces and knowledge acquired from figural spaces comes from individual differences. Spatial ability measured with paper pencil test, i.e., tasks in figural space, have been found to correlate only weakly with tasks such as pointing or wayfinding taking place in environmental spaces. These correlations are even smaller than subjective reports of sense of direction (Hegarty et al., 2002; Hegarty & Waller, 2005). Good performance in figural spaces is hence not necessarily associated good performance in environmental spaces.

2.4.6.4 Knowledge acquired from verbal descriptions

Spatial knowledge acquired from verbal directions is always acquired indirectly. As with the encoding of figural spaces, we cannot go into the details of language comprehension in the current discussion (see e.g., Friederici, 1999; Gernsbacher, 1994; Hemford & Konieczny, 2000). One aspect, however, should be mentioned. Most researchers agree that we construct mental models during language comprehension (e.g., Hemford & Konieczny, 2000). Such mental models are internal representations of the state of affairs in the outside world (e.g., Johnson-Laird, 1980; 1983). They can be seen as isomorphic mappings of external entities and their spatial or non-spatial relations. During reading we construct such mental models and use them to draw inferences (e.g., Knauff & Johnson-Laird, 2002). The process of constructing mental models during reading results in specific errors when drawing inferences (e.g., Jahn, submitted). Most experiments investgate possible arrangement of objects within a vista space. There are, however, also experiments investigating environmental spaces. For simple environments participants draw inferences and draw maps equally well regardless of whether the environment was described from route or from survey perspective or learned from a map. Contrary to this, the verbatim statements themselves are verified better from the same perspective than from other perspectives (Taylor & Tversky, 1992). The results indicate that participants formed similar mental models which most likely involved the construction of a figural space (cf. Denis & Zimmer, 1992). However, differing results were reported where descriptions in route perspective led to better performance (Ferguson & Hegarty, 1994; Perrig & Kintsch, 1985). In addition, switching perspectives while reading a text is associated with increased reading times (Black, Turner & Bower, 1979; Lee & Tversky, 2001; 2005). This indicates that perspective can play a role in the construction of mental models from descriptions.

Applying verbal directions for finding a route leads to better performance when focusing on actions and landmarks (e.g., Denis, Pazzaglia, Cornoldi & Bertolo, 1999). Maps and verbal route instructions lead to similar wayfinding performance (Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000). This might indicate similar knowledge is acquired via these two indirect sources.

2.4.6.5 Knowledge acquired from virtual environments

Virtual environments differ in their level of similarity to experiencing real environments as a function of particular characteristics, i.e., the field of view, the availability of depth cues, the level of photorealistic detail, or the availability of additional modalities such as bodiliy cues, sound etc. For example in a desktop virtual environment the field of view is rather small and the navigator lacks inertial cues. In an immersive virtual environment using a head-mounted display, the field of view can be much larger, visual depth cues such as stereo vision and motion parallax are available as are inertial cues while actively walking through the environment. Therefore, a large variability in the knowledge acquired from such different setups can be expected. Many virtual environments are not a copy of a real environment, so the virtual environment is the only source of knowledge and can be considered as a direct experience. As with figural spaces experiencing virtual environments can be distinguished in direct and indirect experience.

Virtual environments as a direct source of knowledge. Knowledge acquired from a virtual environment is more similar to knowledge acquired from real environmental or vista spaces, than to knowledge acquired from figural spaces.

People form similar knowledge from real and virtual environments which is different from map learning. For example maps lead to orientation specificity whereas navigation in real and virtual environments usually does not. (Richardson, Montello & Hegarty, 1999; Rossano et al., 1999; Ruddle, 2000; Sun, Chan & Campos, 2004; Tlauka & Wilson, 1996).

As knowledge acquired from environmental spaces, knowledge acquired from a virtual desktop environment is asymmetric. For routes learned only in one direction the recognition of landmarks is primed more strongly into the direction they were learned than into opposite direction (Schweizer, Herrmann, Janzen & Katz, 1998; Janzen, 2006).

Compared to real environments participants generally underestimate static distance (e.g., Creem-Regehr, Willemsen, Gooch & Thompson, 2005; Henry & Furness, 1993; Knapp & Loomis, 2004; Lampton et al., 1994; Witmer & Kline, 1998; but see Waller, 1999). This is not due to a limited field of view (e.g., Creem-Regehr et al., 2005; Knapp & Loomis, 2004).

Even with simple desktop virtual environments participants are able to learn route and survey knowledge. Compared to real environments performance is worse for survey measures such as pointing or Euclidean distance estimation, but not so much for route knowledge such as route distance estimation (e.g., Henry & Furness, 1993; Richardson, Montello & Hegarty, 1999; Sun, Chan & Campos, 2004). With extensive training similar survey knowledge can be acquired (Ruddle, Payne & Jones, 1997). To a probably large extent the limits acquiring survey knowledge are due to missing body cues in these studies (cf. Péruch & Gaunet, 1998; see also 2.3.1.3). In survey knowledge tasks participants perform better with a head mounted display allowing to turn or even walk around compared to a desktop virtual environment (e.g., Chance, Gaunet, Beall & Loomis, 1998; Ruddle & Lessels, 2006; Ruddle, Payne & Jones, 1999). Apart from being able to move and turn another aspect might contribute to the better performance in virtual environments experienced with head mounted displays. The interferrence between such immersive environments and the real world, i.e., the room the experiment is taking place, is diminished probably leading to better performance (cf. May, 1996; 2000).

Compared to learning survey knowledge from a map, acquiring survey knowledge from a virtual environment is generally worse (Richardson et al., 1999; Waller, Hunt & Knapp, 1998). Knowledge acquired from maps is orientation specific whereas knowledge acquired from virual environments usually is not (Richardson, Montello & Hegarty, 1999; Ruddle, 2000; Sun, Chan & Campos, 2004; Tlauka & Wilson, 1996).

The nature of knowledge acquired from virtual environments cannot only be examined by comparing it to knowledge acquired from other sources. In a correlative study participants had to accomplish several survey knowledge tasks for knowledge acquired from direct experience, a video or a desktop virtual environment (Hegarty, Montello, Richardson, Ishikawa & Lovelace, 2006). Performance when learning from one source was correlated with performance when learning from another source. Measures for knowledge from direct experience defined a separate factor from measures of learning based on video and virtual environments. In structural-equation models spatial ability tests conducted in figural spaces predicted the performance on learning from video and virtual reality more strongly than direct learning. This indicates that survey learning from video or virtual desktop environments is more similar to learning from figural spaces than to learning from real environments. As mentioned before, this is not necessarily generalised for more immersive virtual environments which use larger field of views and where one can walk through.

In general, knowledge acquired from virtual environments is similar to knowledge aquired from real environments with respect to route knowledge and orientation specificity although the errors are usually larger in virtual environments. For survey knowledge, clear differences have been found in desktop virtual environments which might be less pronounced in more immerersive virtual environments.

Virtual environments as an indirect source of knowledge. To some extent similar knowledge is acquired from real and virtual environments, these virtual environments can be used to learn something about their real conterpart. Several studies show that transfer of knowledge from virtual to real environments takes place (e.g., Bliss, Tidwell, & Guest, 1997; Darken & Banker, 1998; Regian, Shebilske & Monk, 1992; Waller, Hunt, & Knapp, 1998; Wilson, Foreman & Tlauka, 1997; Witmer, Bailey, Knerr & Parsons, 1996; but see Kozak, Hancock, Arthur & Chrysler, 1993). With extented training in virtual environments participants can even walk a route blindfolded in shorter time than participants who had been trained in the corresponding real environment for shorter time (e.g., Waller, Hunt & Knapp, 1998). However, with similar training performance usually is better for training in real environments compared to both desktop and more immersive virtual environments (Waller, Hunt & Knapp, 1998; Wilson, Foreman & Tlauka, 1997; Witmer et al., 1996).

The degree of transfer depends on various variables such as the immersivness, the features displayed or the task conducted. Better knowledge transfer to the real world can sometimes be observed with head mounted displays than with desktop presentation (e.g., Grant & Magee, 1998; but see Waller, Hunt & Knapp, 1998). Also the amount of features represented in the virtual environments plays a role. With training in a simple desktop virtual environment features additional to mere geometry of houses such as paths or fences enhance pointing performance on the corresponding real campus afterwards (Chabanne, Péruch & Thinus-Blanc, 2003). Probably route knowledge is transferred more easily than survey knowledge (Bliss, Tidwell, & Guest, 1997; Witmer et al., 1996). For a reorientation task in a vista space children show clear transfer from the virtual to the corresponding real environment (Foreman et al., 2000). However, no transfer was found in a task where adults had to pick and place objects (Kozak, et al., 1993). With extensive training, transfer in children for a pointing task in a real building is better when learning the building from a desktop virtual environment than when learning it from a model (Foreman, Stanton, Wilcon & Duffy, 2003).

2.4.6.6 Summary

Spatial knowledge acquired from different sources has similar properties for all sources, however, pronounced differences are also found. Similarities are most likely due to the spatial character of all spatial knowledge which distinguishes it from other kinds of knowledge such as social or skill-based knowledge. Probably only spatial knowledge is orientation-dependent, encoded within a frame of reference, biased to a certain extent and easily expressed within two or three dimensions. Such basic similarities may be reflected in similar or common representations and similar or common very basic mechanisms operating on them. Similarities between knowledge acquired from figural, vista, or environmental spaces on one side and verbal descriptions of spaces on the other side can be explained with the spatial nature of mental models constructed from the verbal descriptions.

Apart from the similarities for all spatial knowledge, there are, however, also differences. Figural, and environmental spaces differ in the kind of orientation dependency. Figural spaces usually have well-defined borders, which are less precisely in vista spaces and often rather difficult in environmental spaces. The concept of a continuous, integrated cognitive map can be applied to figural and vista spaces, not so, however, to environmental spaces. Concepts such as route knowledge, survey knowledge or orientation strategies only make sense for environmental spaces or representations of them, but not for figural or vista spaces per se.

Acquiring knowledge about a space indirectly via representations of that space such as maps or verbal directions is likely to be a specific human capability. Interestingly the representation almost exclusive works in one direction. Environmental or vista spaces are not used to learn something about figural spaces, it works the other way round. When using knowledge acquired indirectly, transformation processes take place. Virtual environments can be seen as falling in between direct and indirect experiences. Depending on the setup they show more similarity with knowledge acquired from figural spaces on the one hand or vista and environmental spaces on the other.

The differences in knowledge about different kinds of spaces most likely correspond to different representations or mechanisms. For representations such a possibility will be explored in the next section.

2.5 Representations

In Section 2.4 we looked at different properties of spatial knowledge, e.g., orientation specificity, or frames of reference. Such properties can be realised in various ways: by different representation, by different processes working on the same representation (cf. Craik & Lockhart, 1972), or by a combination of both. We discussed processes and strategies involved in orientation in Section 2.3. Now we will discuss different kinds of representations of spatial knowledge. We will, first, define the term representation, second, give an overview over the imagery debate which discussed the necessity of assuming perception-like representations, and third, we will discuss representations assumed by working memory theory. Note that not all possible distinctions between representations are considered.

2.5.1 Definition of representations

Following Vosgerau (submitted) we define a representation as a substitute of an argument in a function. A function here is seen in the mathematical sense, not in a teleological sense which would encompass serving a purpose. A function is simply a maping relation. Inputs and current states are mapped to subsequent states and outputs such as overt behaviour. For example such a function can map a frog and a fly in front of the frog onto a tongue movement towards the fly. As we know, the frog perceives the fly and this percept ultimately triggeres the tongue movement. This percept of the frog is a substitute of the fly and hence a representation of the fly.[17] A representation represents something, because it takes over its functional role. It stands for the represented object. This functional account implies always a relation to behaviour. Therefore, a city map should only be considered as a representation of a city as something is done with the map. Words are representations, as are physical or mental pictures. An additional property of a representation is that a representation can be more appropriate or less appropriate. Misrepresenting a cow in fog as a horse is an inappropriate representation. It is, however, a representation. Alternative conceptions of representations by causation (e.g., Fodor, 1987) or by isomorphism (e.g., Palmer, 1978; Shepard & Chipman, 1970) have problems in considering misrepresentations as representations (cf., Rothkegel, 1999; Vosgerau, submitted).

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[17] In fact, the representation is better described as a representation of a fast moving dark object, which is probably the best description or ‚normal function' as described by Biology (cf. Lettvin, Maturana, McCulloch & Pitts, 1959). More precisely representations have to be seen as substitutes in such normal functions not in any kind of functions.

2.5.2 Descriptive versus depictive representations: the imagery debate

In the 1970's the so called "imagery debate" emerged about the question whether depictive (or perception-like) representations exist additional to descriptive (or language-like) representations (e.g., Paivio, 1971; Kosslyn, 1980; Pylyshyn, 1973; for an overview see Block, 1981; Tye, 1991). Descriptive representations have been referred to as propositional representations. A proposition can be seen as a basic element in a verbal expression, e.g., a description of a room. A proposition is the minimal possible unit carrying meaning. This meaning is independent from how it is expresses in words, e.g., "the picture is red", "red picture" etc. Therefore, a proposition can be judged right or wrong depending whether the picture is in fact red or another colour.

Alternatively, a depictive representation has some resemblance to the entity it represents. Its structure is similar or analogous. For example, distance, form, or orientation are reflected in the representation, like when imagining the tree in front of our house. The depictive representation is not an arbitrary assignment which is the case for descriptive words, e.g., the words "tree", "arbre" or "Baum" themselves have no resemblance to the tree in front of the house. No true or false value can be assigned to a depictive representation. Depictive representations can be described with part-whole relationships, which is not the case for descricptive representations. For example in a picture the head of a mouse is part of the mouse and is located with relation to the rest. However, in descriptions the letter "m" in the word "mouse" does not represent a part of the mouse. Each portion of a depictive representation corresponds to a representation of a portion of the object, such that the distances (defined within the metric of the representational space) among the representations preserve the corresponding distances among the represented portions of the object (Kosslyn, Ganis & Thompson, 2003).

2.5.2.1 Arguments for depictive representations

It was debated whether or not depictive representations exist in addition to descriptive ones. Nobody seemed to question the existence of descriptive representations. Several effects were used to argue for the existence of depictive representations Amongst others, these effects were mental scanning, spatial priming, distance comparison, mental rotation and the picture superiority effect.

The picture superiority effect shows that memory for pictures is better than for the corresponding words. This is the case for the recall and the recognition of single objects (e.g., Kirkpatrick, 1894; Madigan, 1983). Imagining one or more objects presented verbally leads to better memory performance compared to just focusing on the words, even more so when several objects can be integrated into one scene (e.g., Bower, 1972). Verbal descriptions that can be arranged spatially are recalled better than descriptions which have to be remembered by the words only (e.g., Brooks, 1967). In mental scanning, subjects mentally scan over a visual image learned from a picture or verbal descriptions. It has been shown that the greater the distance between two points the longer is the corresponding scanning time. This was interpreted as evidence for a metric structure of the representation (e.g., Denis & Zimmer, 1992; Finke & Pinker, 1982, 1983; Kosslyn, Ball, & Reiser, 1978). Similarly reductions in performance time due to spatial properties have been seen as arguments for depictive representations. Priming with close-by objects reduces recognition time. This reduction is greater the smaller the distance is between the prime and the tested object, as long as both are located within one region (e.g., McNamara, 1986). In mental rotation the time to judge whether two three-dimensional objects are identical depends linearly on the angle between the two perspectives (e.g., Shepard & Metzler, 1971). Similar increases in time were found when mentally folding paper depending on the number of folds required (Shepard & Feng, 1972). When judging which of two animals is taller the speed of decision is higher for larger differences between the animals, e.g., participants react faster for the pair elephant-mouse than for the pair horse-dog (e.g., Paivio, 1975). More recent results from neuroimaging indicate that early visual areas involved in visual perception are also active during mental imagery (e.g., Kosslyn, Thompson, Klm & Alpert, 1995; Kosslyn et al, 1999). These early areas are topographically organised and the pattern of activation depends on the spatial properties of what is visualised (e.g., Kosslyn et al, 1995). This indicates a correspondence between how the physical space neurons in the brain are organised and the mental space occupied by the imagined object.

2.5.2.2 Arguments against depictive representations

The main arguments against depictive representations came from Pylyshyn (e.g., 1973; 2003a; 2003b). His basic argument against depictive representations is that when asked to imagine something, people ask themselves what it would be like to see it, and then simulate as many aspects of this event as they can and as seem relevant. This explanation does not make any assumptions about the format of the representation. Better memory after imagining an object can be due to general context effects, i.e., different encoding strategies, which does not necessarily argue for a depictive representation. Also the activation of early visual areas during imagination does not imply that the underlying functional representation is depictive. These neuronal areas are organised retinotropically, i.e., two dimensional, but Pylyshyn argued mental images often are three dimensional like in the case of mental rotation.

Contrary to perceptions which have to be interpreted, mental images are always interpreted. In fact they are difficult to reinterpret based on their visual properties , e.g., we do not recognise another figure after mentally rotating a picture, however, we do so easily after physically rotating the picture (e.g., Slezak, 1991).

However, reinterpretating a picture after mental rotation is possible (e.g., Rouw, Kosslyn & Hamel, 1997). Pylyshin argues mental rotation does not have to be continuous. Computing a new representation from a different angle does not have to involve rotation at all. Iteratively computing slightly new perspectives might show increased reaction times for greater angles which does not necessarily require a depictive representation. Even if rotation was involved in mental rotation, this does not necessarily imply that the underlying representation is depictive.

In summary, Pylyshin argues that reasoning with images is different from reasoning about other areas, however, one does not necessarily have to assume a depictive representation to explain that. He argues that general problem solving using propositional representations is sufficient. He also argues that our subjective phenomenal impression when imagining a tree can be seen as an epiphenomenon which is not relevant for explaining, e.g., reasoning about the tree.

2.5.2.3 Conclusion

A wide range of experimental results has been associated with depictive representations. Pylyshin argued, that these results can also be explained without assuming that depictive representations exist in addition to descriptive ones. From the point of view of philosophy of science, this dispute cannot be decided empirically only (cf. Anderson, 1978). It is argued that all empirical results can be explained assuming just one representation may it be it depictive or descriptive. The explanations may differ in their complexity due to how many additional assumptions they have to make, but an alternative explanation can never be excluded. So predicting a result which cannot be predicted by the other theory is not possible. However, the explanations can differ in complexity. Applying Occam’s razor one could decide for the simpler explanation. Please note that the simpler explanation is not per se identical with assuming fewer representations. Assuming only one representational format, but having to assume many additional processes or many distinctions for different materials can be more complex. In that sense, alternative explanations for the mentioned effects using only descriptive representations are probably more complex than explanations assuming both a descriptive and a depictive representation.

This also applies for the developmental continuity assumed in this work. If adult performance can merely be explained by descriptive representations then performance in human children and in non-human animals must also be explained by descriptive representations only. Otherwise there has to be a switch from another kind of representational format in non-human animals and human children towards the exclusive use of descriptive representations in human adults. There is no indication in developmental psychology for such a shift. An alternative to a developmental switch is the exclusive existence of descriptive representations in human children and non-human animals which is counterintuitive, too. Would it apply to all animals? Or would there be a switch such as the one indicated also between "lower" and "higher" animals? Such problems with complete switches between representations not apply the other way round. Non-human animals and human children can interact with the world relying on depictive representations only. At one point in human development descriptive representations develop and can be used in addition to depictive ones in order to solve problems in daily life and in laboratory experiments. Along with the development of language probably descriptive representations would emerge. In summary, we think that assuming descriptive *and* depictive representations is the simpler explanation for the developmental perspective as well as for the various effects such as mental scanning, the picture superiority effect, etc. compared to assuming descriptive representations only.

The debate on whether there are depictive representations was quite restricted to representations and often did not consider how these representations are processed. On the other side, the debate was quite unfocused regarding the time aspects of representations. Priming and the picture superiority effect are aspects of long-term memory whereas mental rotation is rather concerned about aspects of short-term memory. On the contrary working memory theory also refers to the distinction between representations or memory systems, however, it focuses explicitly on short-term aspects and also takes processing into account (e.g., Miyake & Shah, 1999). We will discuss working memory in the next section.

2.5.3 Working memory

Working memory theory assumes a limited capacity system, which temporarily maintains information and supports human thought processes by providing an interface between perception, long-term memory and action (e.g., Baddeley, 2000; 2003; Baddeley & Hitch, 1974; Miyake & Shah, 1999). Compared to other theories concerning short term storage systems (e.g., Atkinson & Shiffrin, 1968), working memory theory emphasises combined storage and processing and working memory theory distinguishes between several subsystems. Although there are various working memory theories (cf. Miyake & Shah, 1999) most of them agree on the need for a system of limited attentional capacity, supplemented by more peripherally-based storage systems (Baddeley, 2003). In the original version of working memory theory by Baddeley and Hitch (1974) the control system of limited attentional capacity, is termed the central executive. It is assisted by two subsidiary storage systems: the phonological loop and the visuospatial sketchpad.

2.5.3.1 The phonological loop

The phonological loop consists of a phonological store (which can hold memory traces for a few seconds before they fade), and an articulatory rehearsal process (that is analogous to subvocal speech) (e.g., Baddeley, 2003). Memory traces can be refreshed by being retrieved and re-articulated. Immediate memory has a limited span because articulation takes place in real time. As the number of items rehearsed increases, a point is reached at which the first item will have faded before it can be rehearsed.

Evidence for the phonological loop comes from the phonological similarity effect, the word-length effect and the irrelevant speech effect. When keeping unrelated letters in the phonological loop, similar sounding letters such as V, B, or G are recalled less well then dissimilar letters, such as W, X, K (Conrad, 1964; Conrad & Hull, 1964). The similarity of sounds is also crucial for unrelated words, whereas meaning is relatively unimportant (Baddeley, 1966). These results indicate that the code is acoustic or phonological and not semantic. The immediate memory span of words declines as word length increases (Baddeley, Thomson & Buchanan, 1975), which suggests articulatory rehearsal. The presentation of irrelevant speech impairs the immediate recall (e.g., Salame & Baddeley, 1982). However, also variable tones can produce the effect (e.g., Jones & Macken, 1993) suggesting that it is not necessarily language related. In addition, the phonological similarity effect and the word-length effect depend, to a certain extent, on material without semantic meaning and break down when semantic coding can be used (e.g., Papagno & Valar, 1992). These results suggest that the phonological loop might be a stage in language comprehension and can facilitate the acquisition of new languages (Baddeley, Gathercole & Papagno, 1998).

2.5.3.2 The visuospatial sketchpad

In the working memory model by Baddeley and Hitch (1974) the visuospatial sketchpad was seen as a subsystem for storing visuospatial information. It is limited in capacity to about three or four objects, as indicated in experiments in change blindness (e.g., Simons & Levin, 1997). In such experiments objects in scenes change appearance, move or disappear without people noticing. Such a rather strong limitation of the visuospatial sketchpad was explained with the rich and persistent visual input which makes detailed visual retention largely redundant (Simons & Levin, 1997). This conception regards working memory as an input buffer getting information from sensory inputs. However, we will discuss recent developments proposing changes in the temporal position of working memory in the information process, and assuming a distinction between visual and spatial components.

Visuospatial working memory and sometimes also other working memory systems are no longer seen as a temporary buffer between sensory input and long-term memory anymore (cf. Baddeley & Hitch, 1974; Atkinson & Shiffrin, 1968). Instead, it is thought that information from sensory input has to be processed with the participation of long-term memory first before accessing working memory. Therefore, visuospatial working memory is viewed as a mental workspace where information can be made available in an interpreted form (e.g., Logie, 1995; Logie & Della Sala, 2005).

Visuospatial working memory has been divided further into a visual and a spatial component. Evidence for this distinction comes from behavioural double dissociations, lesion and fMRI studies as well as from the visual impedance effect. Theses double dissociation experiments use two visual working memory tasks such as recalling patterns or discriminating colours and two spatial working memory tasks such as recalling locations on a screen or tapping blocks on a table. The two spatial tasks should interfere more strongly with each other than with one of the visual tasks. Similar the two visual tasks should interfere more strongly with each other than with the spatial tasks. This pattern of result was found in various experiments (e.g., Della Sala, Gray, Baddeley, Alamano &Wilson, 1999; Logie & Marchetti, 1991; Quinn & McConnell, 1996; Klauer & Zhao, 2004). In neuropsychology, patients with brain lesions have been reported showing either disruption of visual, but not spatial working memory, or the opposite pattern (e.g., Carlesimo, Perri, Turriziani, Tomaiuolo & Caltagirone, 2001; Farah, Hammond, Levine & Calvanio, 1988).[18] Similarly, different brain activations for spatial and visual tasks have been observed in fMRI studies (e.g., Owen et al., 1998). In addition, the visual impedance effect indicates a distinction between visual and spatial working memory: participants show worse performance in reasoning tasks when they are asked to imagine visual properties, but not so when they imagine spatial or both visual and spatial properties (Knauff & Johnson-Laird, 2002). All these results indicate that a spatial and a visual working memory component are dissociable.

Various interpretations exist on what exactly the visual and spatial components are. First, visual working memory can be seen as concerned with surface properties. It is specifically associated with visual input. Contrary to that, spatial working memory is regarded as a modality-independent abstract representation of spatial relations to which various sensory inputs can contribute (cf. Knauff, 1997; Kosslyn, 1994; Bryant, 1992). Similar performance for spatial working memory tasks after visual and auditory stimuli supports this view (Lehnert & Zimmer, 2006).

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[18] The neuronal and the functional level are two levels of description. We will not discuss problems regarding the interaction or theoretical reduction between these levels of descriptions, but just assume a close connection. We will, therefore, use data from each level as indications for fractioning within the functional theory of working memory.

In a second interpretation the visual working memory can be seen as concerned with object features and their location, whereas the spatial working memory is concerned with the location of objects (e.g. Smith & Jonides, 1997). This interpretation is consistent with the "what" and "where" pathways in the brain (Ungerleider & Mishkin, 1982; Mishkin, Ungerleider, & Macko, 1983). The "what" pathway is concerned with the identification of objects and would correspond to the visual working memory. The "where" pathway is more concerned with location in space and would correspond to the spatial working memory. This interpretation is similar to regarding visual working memory as concerned with figural spaces, whereas spatial working memory as concerned with vista spaces.

A third interpretation regards visual working memory as static and spatial working memory as dynamic (e.g. Logie, 1995; Logie & Della Sala, 2005; Pickering, 2001). In this interpretation visual working memory refers to the appearance of an object or a scene, e.g., its colour, shape contrast, size, visual texture and to the location of objects relative to one another in the scene with respect to a particular viewpoint in a static array. Contrary to that, spatial working memory refers to pathways or sequences of movements from one location to another in the scene or the processes of change in the perceived relative locations of objects that occur when an observer moves (physically or in mental imagery) from one viewpoint to another. Within this conception positions assuming a motor dimension in memory would also be described (e.g., Smyth & Pendelton, 1990; Engelkamp & Zimmer, 1994).

The visuospatial skechpad is involved when dealing with visuospatial material. It's capacity was proposed as a non-verbal measure of intelligence which correlates with success in fields such as architecture and engineering (Baddeley, 2003). It's contribution to spatial orientations seems likely, however, little research has been done to investigate this relationsship.

2.5.3.3 The central executive

The central executive originally was treated as a pool of general processing capacity, to which all issues not related with the phonological loop or the visuospatial sketchpad were assigned (e.g., Baddeley & Hitch, 1974). This was comprised of memory content as well as aspects related with processing memory content. In more recent conceptions the central executive has been associated with executive functions such as focus, divide and switch attention and connect working memory with long-term memory (e.g., Baddeley, 1996). However, various points often remain underspecified, e.g., how the proposed functions work exactly, including the concrete interaction with the subsystems and with long-term memory. Recently a third subsystem, the episodic memory has been proposed to account for some of the problems (Baddeley, 2000).

2.5.3.4 Working memory in spatial orientation

Concerning figural spaces a distinction between a visual and a spatial working memory component were already explained. In addition, different involvements of verbal and visuospatial working memory components can be found in interaction with map-like figural spaces. Learning and recognising nonsense words is affected more strongly by articulatory suppression than by spatial tapping whereas learning and recalling a route from a map the opposite pattern is indicated (Garden, Cornoldi & Logie, 2002). Counting backwards interfered more strongly with non-spatial descriptions than with spatial descriptions of a figural space (cf. Brooks, 1967), the opposite pattern was found for memorising the presentation sequence of objects on a screen (Pazzaglia & Cornoldi, 1999). Therefore, the visuospatial working memory seems to be involved in the processing of figural spaces more strongly than verbal working memory.

Contrary to figural spaces the results of studies concerning working memory in vista and environmental spaces are rather diverse. Learning locations along a route is disrupted by a backwards-counting task compared to no additional task (Lindberg & Gärling, 1982). Backwards-counting interfered more strongly with updating in a triangle completion task than verbalising nonsense sounds (May & Klazky, 2000). These results can be interpreted as an involvement of the central executive during updating which is occupied more strongly during backwards-counting than during mere verbalising. Blindfold navigation of a route indicated by spatial sound is less vulnerable to a tactile n-back cognitive load task than navigating this route with verbal commands (Klatzky, Marston, Giudice, Golledge & Loomis, 2006). This can be interpreted with more cognitive requirements during the verbal commands compared to more direct perceptual guiding during sounds. The memory for a route description through a zoo degraded more strongly during memorising the presentation sequence of objects on a screen than during detecting changes in object location in two successively presented pictures. Contrary, no differences in memory due to these tasks are found for a mere visual description of a zoo (Pazzaglia & Cornoldi, 1999). This might relate with differential influence of visual and spatial working memory. For learning and retracing a route through a town while performing a secondary task, participants performed equally well with an articulatory suppression task and a spatial tapping task (Garden, Cornoldi & Logie, 2002).

Taking these results together, no clear picture of the contribution of working memory systems to the interaction with vista or environmental spaces can be drawn. One possible reason for the conflicting results is probably the involvement of verbal strategies for navigating routes (cf. Garden, Cornoldi & Logie, 2002). As the difficulty of the secondary tasks was not controlled in most studies, observed effects might also originate simply from easy versus difficult secondary tasks rather than from the involvement of different working memory systems. Another reason could be due to the fact that almost all visuospatial working memory tasks are concerned with interaction with figural spaces. However, different memory systems might exist for representing figural, vista, and environmental spaces. Alternatively or additionally different processes might process these kinds of information. In that sense mental rotation could act on representations of figural spaces whereas perspective shift could act on representations of vista or environmental spaces (Kozhevnikov & Hegarty, 2001).

2.5.3.5 Summary

As argued in the section regarding depictive and descriptive representations, we think it does make sense to assume multiple representations. Working memory theory provides a framework for that, specifying the individual representations as well as taking processing aspects into account. Several working memory systems have been proposed. The central executive is taking control functions. The phonological loop is a temporal storage and rehearsal system for phonological material. It might be involved in orienting when applying verbal strategies. The visual working memory concerned with static object cues such as surface texture, form, or colour can be distinguished from spatial working memory which is more concerned with dynamic aspects and/or modality-independent spatial relations between objects. Visual and spatial working memory is involved in the interaction with figural spaces. Their relevance for interacting with vista and environmental spaces is probable, but largely unknown.

2.6 Strategies for orientation in environmental spaces

Chapter 2 reviewed the literature about spatial orientation. We now want to summarise the results regarding the strategies used by human navigators for orienting in environmental spaces. We will point out open questions and explain how our experiments are suited to answer them.

Section 2.2 described the goals pursued by navigators. Reorientation, for example, is the goal to determine one's location and orientation in the environment after getting lost. Contrary to that, navigators are oriented during wayfinding. They know where they are and they know where they are heading towards. The required knowledge for wayfinding and reorientation is either obtained from external representations like maps or route directions or it is provided by internal representations, i.e., memory. When getting lost during wayfinding, navigators have to reorient first before being able to again approach their goal location. Exploration as the goal of learning something about the environment and systematic search as a way to track down something at an unknown location will not be discussed further here. For humans and non-human animals several orientation mechanisms have evolved to reach a goal like reorientation or wayfinding (2.3.1.1). We identified updating, route navigation and reorientation as the most relevant.

In Section 2.3.1.2 we described the importance of landmarks and the geometric layout for reorientation. The geometric layout is considered more important than landmarks. Humans and most other animals use distances and angles to find locations again. Language eases reorientation on geometry, but is not necessary. Hippocampal place cells can be seen as a neural representation of a location in a vista space. For non-human animals reorientation seems to rely on features of specific vista spaces. Contrary to that, humans seem to be able to reorient on maps and on the spatial structure of an environmental space.

In Section 2.3.1.3 we described updating by path integration as an orientation process in which self-motion is integrated over time to obtain an estimate of one's current position in space. When moving physically, updating happens automatically and leads to better performance especially when turns occur. Interference can explain the drop in performance for imagined updating compared to physical updating as well as problems with virtual environments. Online updating by path integration is an error prone working memory process. In humans accurate updating is limited to rather short distances. Movement trajectories can also be stored in long term memory.

In Section 2.3.1.4 we described route navigation. Route navigation allows reaching a goal in an environmental space by a travelling a known route. It involves identifying a location in the environment and then selecting a direction along a possibly looped route leading to the goal. Identifying a location and selecting a direction is repeated several times before a goal is reached. Route navigation is based on discrete locations, not on a continuous representation of the environment. It is not learned for one certain goal, but location to location information is learned. This can constitute a network structure of locations connected with 'move-to-information'. The where-to-move part is an abstract direction information, e.g., expressed by a vector, rather than a specific behaviour. The knowledge necessary for route navigation is called route knowledge and can be learned by directly experiencing an environment or indirectly via maps, verbal descriptions etc.

In Section 2.3.1.5 we showed that reorientation, updating and route navigation have a clear dominance order when two of them can be applied at the same time. Reorientation and route navigation dominates over updating, i.e., navigators do not use information from updating by path integration when other conflicting information is available. Updating therefore, can be considered as a backup strategy when other processes fail. It can, however, contribute to the mental representation of an environment. Navigators only apply wayfinding when they know their goal and specific location in an environment, whereas they will have to reorient before being able to use route navigation in order to reach their goal.

Therefore, reorientation and route navigation do not conflict, they can, however, use the same representations.

We argued that human and non-human animals use the three described processes for orientation. However, humans show a much larger variability and flexibility in orientation behaviours (2.3.2). We proposed especially two reasons for that (2.3.2.1). First, humans are able to use multiple representations for orientation. They can orient not only based on their internal representations acquired during experiencing an environment, but they can use external representations like maps, verbal descriptions etc. External representations are a common way to communicate spatial knowledge. Humans can use them directly, however, humans can also memorise such representations and use them for orientation purposes. Aside using other representations for orientation, humans are able to plan differently. Humans are not bound e.g., to an activation spread mechanism proposed for selecting a route in non-human animals, but they can also use planning in the sense of searching through a problem space. More flexible planning and being able to use multiple representations for spatial orientation opens a variety of new options for orientation. Probably the most prominent of these options is survey navigation. During survey navigation new shortcuts are used to approach a goal without relying on updating or visible landmarks. However, along with multiple strategic options like survey navigation, there also comes the necessity of deciding among them. If the orientation processes in non-human animals seem clearly prioritised, there is a vast amounts of strategies humans can possibly apply in a situation including the options also available for non-human navigators. Humans have to decide, which one to use in order to solve their orientation problem. Such a selection probably depends on various factors like, the available information, the costs for using this information, environmental constraints, or individual preferences. The following studies aim to clarify some of the circumstances under which a specific strategy is used.

To organise the studies concerned with strategies for spatial orientation, we need to differentiate between memory and planning strategies. Memory strategies are concerned with the problem of how to memorise information from the environment. A verbal strategy could include encoding verbal descriptions, a visual strategy could mean encoding a visual pattern, a spatial strategy encoding a spatial layout. Not only encoding, recall and encoding rae relevant for memory strategies. For example, transformation processes that are necessary to apply the recalled knowledge for orientation are an important issue (2.4.5).

When certain knowledge is available, e.g., when recalling it from memory or when using external representations like maps, navigators can plan how to reach a goal. Usually this is thought of exclusively as wayfinding or searching (2.3.2.2), but it also applies for reorientation (2.3.2.3). Even though we distinguish between memory and planning strategies they are not completely independent from each other. Certain planning strategies rely on certain memory strategies. For example, in order to make short cuts (survey or least angle strategy), one has to rely on survey knowledge whereas for other strategies like least number of turns, route knowledge is sufficient (2.4.2).

In this thesis we tried to answer some open questions regarding strategies human navigators use to orient in environmental spaces. In order to do so we will first focus on memory strategies (Study 1, Study 2 and Study 3) and then discuss open questions with planning strategies (Study 4 and Study 5).

2.6.1 Study 1: Memory strategies applied for wayfinding

A good deal of research has been conducted regarding how we memorise figural spaces (2.4). Less focus was given on vista spaces and even less regarding environmental spaces. Verbal descriptions of routes have been found to be useful for wayfinding (2.4.6.4) indicating a possible verbal memory strategy. Regarding the wayfinding performance in non-human animals one is inclined to also assume visual or spatial memory are involved in wayfinding. Indeed a visuo-spatial and a verbal secondary task both interfere with the encoding and recall of a route learned by direct experience (2.5.2.4). However, there might be different visuospatial memory strategies. We discussed the distinction between visual and spatial working memory in Section 2.5.3.2. Navigators might encode a visual pattern like a pictorial snapshot or they might rely more on the strategy of encoding an abstract spatial representation, like the geometric layout. Study 1 was directly concerned with this question when learning an environmental space from direct experience (3.1). It used a dual task methodology to create interferences with specific encoding strategies.

2.6.2 Study 2: Does the spatial memory strategy rely on figural spaces?

As Study 1 indicated an involvement of verbal and spatial strategies, Study 2 and Study 3 tried to figure out more precisely which kind of space could have been involved in the spatial strategy – either the figural space of a map or the surrounding environment with the geometry of the surrounding vista space as the immediate available cue. Both possible strategies are related by specific reference frames used to encode the spatial relations (2.4.5). Retrieving information from an encoded figural space or vista space requires a transformation processes in order to use this information for orientation in environmental spaces. These transformation processes involve alignment with the current environment for vista and figural spaces and a perspective shift from birds-eye view to horizontal view for figural spaces. If navigators use a map-encoding strategy the mentioned transformation costs should occur for wayfinding as well as for route and survey knowledge tasks performed in horizontal perspective. However, these transformation costs should not occur for route and survey knowledge tasks performed in the same birds-eye view as the encoded map. To test these predictions the encoded map-perspective has to be similar for all participants. Therefore, participants in Study 2 learned the routes through an environmental space from a map before being tested in the various tasks (3.2). As a control we used instructions from verbal directions. So far no clear differences between these kinds of instructions were observed for wayfinding tasks (2.4.6.4). We, therefore, additionally tested whether memory strategies depended on the environment by using two different routes.

2.6.3 Study 3: Does the spatial memory strategy rely on vista spaces?

Study 2 tested whether the spatial memory strategy for encoding environmental spaces is concerned with figural spaces. Study 3 tested the whether the spatial memory strategy was concerned with vista spaces (3.3). As indicated by studies on reorientation (2.3.1.2) and in studies using isovist analysis (2.4.6.2) the local geometry of a vista space might play a role in spatial orientation. The purpose of Study 3 was to test whether the local geometry of vista spaces is present on the knowledge level. Therefore, it also tested the transformation costs for recognising such a vista space encoded in a specific reference frame. Study 3 also examined the interrelations between memory and planning strategies. Usually decision points, e.g., intersections, are primarily encoded during wayfinding (2.3.1.4). However, does a wayfinder have to encode every decision point? Or can the use of a certain strategy reduce the memory requirement, e.g., a strategy to walk straight on during wayfinding unless recalling otherwise. This strategy would allow to encode primarily intersections that require a turn and let aside intersections that require to walk straight on. Such a strategy refers to both planning and memory. Whether human navigators apply such a strategy to minimise their costs of encoding was tested in Study 3.

2.6.4 Study 4: Familiarity and the efficiency of wayfinding strategies

Study 3 investigated both memory and planning strategies. However, Study 4 and Study 5 were more directly concerned with planning strategies. A vast amount of wayfinding strategies have been proposed that are often difficult to distinguish (2.3.2.3). We therefore focused on three strategies that relate to important distinctions in the literature: survey, route and regional strategies. In Section 2.4.2 we introduced the distinction between route and survey knowledge relating to different strategies. If navigators choose a route strategy, they choose a route through familiar parts of an environment sticking to main corridors. Contrary to that a survey (or least angle) strategy involves making new shortcuts trying to approach the goal as directly as possible. Most results concerning biases in spatial memory can be explained by clustering an environment into regions (2.4.4). Regionalisation, therefore, is a very prominent issue in spatial memory. A regional planning strategy profits from such clustering, e.g., minimising the possible locations required for planning a route, and should theoretically play a prominent role in wayfinding. Therefore, in Study 4, we compared these three strategies within an environment where all of them were applicable and therefore, comparable. In addition, Study 4 investigated whether the applied strategies change for navigators that are very familiar with the environment. Study 4 asked which strategies familiar and unfamiliar navigators apply which strategies lead to better results.

2.6.5 Study 5: Metric and non-metric strategies in wayfinding and reorientation

Just as Study 4 Study 5 looked at route, regional, and survey strategies and used the same setting, i.e., the same building, for that. However, participants did not learn this building by direct experience, but acquired their knowledge about the environment from maps. Comparing data from Study 4 and Study 5 we investigated whether maps can compensate for the lack of familiarity in a wayfinding task. By varying the kind of information present in the maps, we could vary the availability of metric information necessary for applying a survey (least angle) strategy and see whether the survey strategy provided any advantages over a simple or a regional route planning strategy.

In Study 5, we did not only examine wayfinding strategies, but also reorientation strategies. Few studies have investigated strategies to reorient in an unfamiliar environment using maps and even fewer studies have looked at navigator’s strategies to reorient in environmental spaces (2.3.2.3). As was indicated in Section 2.3.1.2, Section 2.4.6.2 and in Study 3 using isovist analysis, the local geometry of a vista space is important for reorientation and wayfinding. Study 5, therefore, examined whether participants’ strategy is to reorient in an environmental space by metric properties like local geometry or whether they rely more on the network of choice points. In Study 5 strategies both for wayfinding and for reorientation underlie a tradeoff between computation and memory costs on one side and preciseness and potency on the other hand. The metric strategies like survey navigation and reorientation by geometry require more resources for applying them, but they might lead to better results than their non-metric counterparts route navigation and reorientation by the network structure. This was tested in Study 5.

2.6.6 Notes on methodology

After providing an overview of the individual studies concerned with strategies navigators use to orient in environmental spaces, we would also like to emphasis two methodological aspects: first, the principle of "methodological triangulation," and second, the external validity. The strategies navigators use to orient in a certain environment and the consequences of their behaviour can be investigated on various levels, i.e., on the level of overt behaviour, the level of knowledge that is acquired by or required for a certain strategy, or on the level of subjective reflection and individual differences. To be able to investigate all three different levels, we measured wayfinding and reorientation performance by measuring navigator's errors, stops, or task completion time, we measured the acquired knowledge using pointing tasks, recognition tasks, alternative choice tasks, and sketch maps, and we determined the applied strategies by looking at the navigators' choice of route, their verbalisations during walking the route or using questionnaires, if those strategies were not already induced by the task itself. We also made sure to control for individual differences. Studies in the field of spatial orientation often focus on one aspect. By performing measures on all these levels, we wanted to "methodologically triangulate" and, therefore, get a more comprehensive picture of strategies for orientation in space.

When investigating how navigators orient in space, it is important to avoid artefacts induced by using highly impoverished laboratory setups. Therefore, to keep the orientation tasks realistic, we decided to use tasks that could be performed in real environments or photorealistic copies of those. In addition, our participants performed wayfinding and reorientation tasks, allowing for direct measurement of such behaviour and not relying on indirect indicators such as pointing or map drawing. These arrangements ensured a high level of external validity, while still keeping experimental control. In order to allow comparisons between the individual studies we kept the environments and tasks as similar as possible. Therefore, the first three studies analysed two wayfinding tasks in the city of Tübingen, Germany or in its virtual model. The last two studies both used wayfinding tasks in a conference centre in Günne, Germany. These two setups allowed covering the two most basic environmental spaces in which we orient in our daily life: towns and buildings.

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3. Experiments

3.1 Working memory in wayfinding

Working memory in wayfinding - a dual task experiment in a virtual city

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Abstract: This study examines the working memory systems involved in human wayfinding. In the learning phase 24 participants learned two routes in a novel photorealistic virtual environment displayed on a 220° screen, while they were disrupted by a visual, a spatial, a verbal or - in a control group - no secondary task. In the following wayfinding phase the participants had to find and to "virtually walk" the two routes again. During this wayfinding phase a number of dependent measures were recorded. We show that encoding wayfinding knowledge interfered with the verbal and with the spatial secondary task. These interferences were even stronger than the interference of wayfinding knowledge with the visual secondary task. These findings are consistent with a dual coding approach of wayfinding knowledge

Keywords: wayfinding – working memory – visual – spatial - verbal – dual task – virtual reality – dual coding

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1 Introduction

> "…it seems plausible to assume that the [visuo-spatial] sketchpad might have a role […] for spatial orientation and geographical knowledge. So far, there seems to have been little work on this potentially important topic." (Baddeley, 2003, p. 834)

The role of working memory in spatial orientation has rarely been explored. Still, is the intuitive impression true that the visuo-spatial sketchpad is so important? If so, is it the visual or more the spatial component of this subsystem that is linked to wayfinding? And how important is the processing of verbal information if humans find their way in known or new environments? In the quotation Baddeley refers to his working memory theory, in which short-term maintenance of information is achieved by the phonological loop (PL), which is responsible for verbal information, the visuo-spatial sketch pad (VSSP), handling visual and/or spatial information, and the central executive which is described as a supervisor responsible for the coordination of the subsystems and the selection of reasoning and storage strategies (Baddeley, 1986, 2003; Baddeley & Hitch, 1974).

So, which subsystem of working memory is essential in human wayfinding? If wayfinders process the wayfinding information in a verbal format, e.g., in the form of verbal directions such as "next left", "at the church to the right" (cf. Couclelis, 1996; Daniel & Denis, 2004; Denis, 1997; Denis, Pazzaglia, Cornoldi & Bertolo, 1999, Lovelace, Hegarty & Montello, 1999), the wayfinding should involve the PL and thus interfere with a verbal secondary task. If the wayfinding knowledge is represented and processed in visuo-spatial format, it should rely on the VSSP. However, recent studies indicate that the VSSP itself has two subcomponents—one visual and one spatial (e.g., Klauer & Zhao, 2004; McConnell & Quinn, 2000). We therefore applied two visuo-spatial secondary tasks. One secondary task focused on the visual component, the other one focused on the spatial component of the VSSP. If the wayfinding knowledge is represented and processed in a "picture-like" format, e.g., in a snapshot of the environment (Mallot & Gillner, 2000) or a map (e.g., Kosslyn, Ball & Reiser, 1978) it should rely on the visual component of the VSSP and thus interfere with a visual secondary task. If wayfinding relies on more abstract spatial representations, e.g., the geometric layout of an environment (Cheng, 1986; Gallistel, 1990; Wang & Spelke, 2002) it should involve the spatial component and interfere with a spatial secondary tasks. The goal of the present paper is to test these competing hypotheses.

2 Methods

We used a virtual environment displayed on a 220° screen. The participants learned two different routes through "Virtual Tübingen" a photorealistic model of the medieval city centre of Tübingen (see Figure 1). During this learning phase they were disrupted by a visual, a spatial, or a verbal secondary task. In the control condition, no secondary task was given. In the following wayfinding phase the participants had to find and to “virtually walk” the two routes with a joystick. No secondary task was performed during that. In this way we could measure secondary task interference with the encoding and maintenance of wayfinding knowledge, while the wayfinding itself was not disrupted by any secondary task.

Figure 1: A snapshot of Virtual Tübingen.

2.1 Participants

Twelve female and twelve male participants, mainly students between 19 and 32 (*M* = 24; *SD* = 4) participated in the experiment. None of them had visited Tübingen before. All selected participants were German native speakers and were paid for their participation. Two of originally 26 participants did not complete the experiment due to simulator sickness and were therefore excluded from all subsequent analyses.

2.2 Procedure, apparatus, and materials

The participants sat on a chair positioned 3.5 meters from a circular 220° screen (width: 13 meters, height: 3 meters), which covered the whole horizontal visual field (see Figure 2). A pc-cluster rendered the projection for an eye position 1.20 meters above the ground referring to average eye-height in when seated. The frame rate was 60 Hz using 2 x hardware anti-aliasing and hardware correction to display the images on the curved screen. Three projectors with a resolution of 1024 x 768 each projected the pictures. Note that learning and wayfinding phases for each route followed one another immediately, i.e., the learning phase for the first route was immediately followed by the wayfinding phase for the first route etc.

Figure 2: The experimental setup.

Learning phase. In the learning phase the participants were passively carried on two routes through Virtual Tübingen. The transportation speed was two meters per second corresponding to a fast walking speed. The 480 meters 'long route' consisted of ten mainly oblique intersections with 23 possible choices (see Figure 3). Its presentation took 240 seconds. With a presentation time of 160 seconds and a length of 320 meters the short route consisted of nine mainly orthogonal intersections, with 21 possible choices (for further discussion of these routes see Meilinger & Knauff, submitted). The order of presentation of the routes was controlled.

While the participants learned a route they were confronted with one of the secondary tasks: the verbal, the visual or the spatial secondary task. In the control group no secondary task had to be completed. We randomly assigned six participants to each of the four groups, ensuring equal number of women and men in each group. All three secondary tasks were presented via headphones with active noise cancellation. The participants had to respond by pressing a button on a response box. To ensure identical stimuli for all participants and in order to be able to measure secondary task performance, the participants watched a video rather than actively navigated the route.

In the *verbal task*, the participants had to perform a lexical-decision task. They had to decide whether a presented word existed in German or not. All 100 German nouns consisted of two syllables and were among the 10000 most frequent German words published in newspapers or magazines (Quasthoff, 1998). The 100 non-words not existing in German language were constructed from the 100 words by exchanging the vowel of the first syllable, e.g., "Montag" was changed to "Mintag". Each vowel was equally often used in the words as well as in the non-words. Therefore 100 non-words paralleling 100 words were constructed. They were spoken by a television speaker, recorded via microphone and cut into 200 sound files with the start of the file matching the onset of the vocalization.

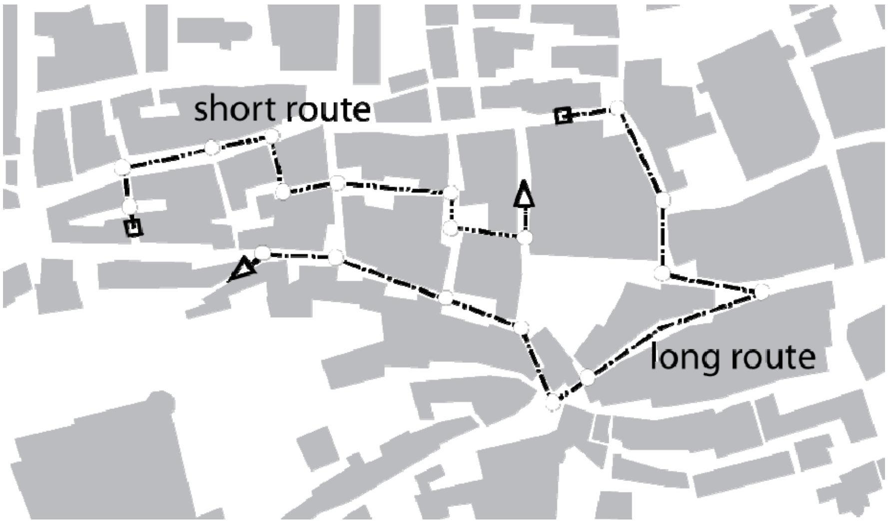

Figure 3: The two routes through Virtual Tübingen used in the experiment. Circles correspond to intersections.

In the *visual task* the participants heard times and had to imagine a clock with watch hands. E.g., at "six o'clock" the short watch hand points downwards, the long watch hand upwards. Dividing the clock in an upper and a lower half, both watch hands point into different halves. At "twelve o'clock" or "twenty past four" both watch hands point into the same half. The participants had to indicate whether the watch hands point to the same or to different halves. All possible times in steps of five minutes were used, e.g., 11:55 with times in the third or ninth hour, e.g., 3:10 and times a quarter to or after an hour, e.g., 5:45 excluded as at these times the watch hands could not easily be classified as pointing upwards or downwards. The resulting 100 times of day again were spoken by a television speaker and cut into sound files which stated with the onset of the vocalization. The participants were explicitly instructed to solve the tasks by imaging the clock.

In the *spatial task* the participants had to indicate the direction a sound was coming, either from the left, the right or the front, by pressing one of three corresponding keys. The pleasant sound of a wooden temple block was used for that. The sound was spatialized using a "Lake DSP Card", with which the sound source can be accurately positioned in space, both in terms of angle and distance to the listener, using a generic Head Related Transfer Function (HRTF). Again, the sound files started with the onset of the sound.

To ensure that the secondary tasks interfered with the encoding of environmental information the task difficulties had to be identical. Therefore, the trial durations were adjusted in within-subject pre tests, so that failing to react fast enough was considered an error. The trials followed immediately after each other with no break in between. Very fast reactions in any trial were ignored, as they possibly were initiated during the last trial. Within-subject pre-tests with 18 participants led to trial durations of 1.2 seconds in the verbal, 4 seconds in the visual and 0.8 seconds in the spatial task. The corresponding hit rates in the pre-tests were 86% for the verbal, 85% for the visual and 87% for the spatial task. The task difficulty was assessed the same way as in the baseline condition of the main experiment, that is while presenting a video showing a walk up and down a street for several times. The area of Virtual Tübingen used for the baseline was not encountered during the rest of the experiment. The participants' task was to keep their eyes open and do the choice reaction task as fast and accurate as possible. In the main experiment all participants, including participants from the control group without the secondary task, had to watch this presentation. The baseline lasted 200 seconds. This is the average of the 160 seconds for presenting the short route and the 240 seconds for presenting the long route. All secondary tasks were presented in random order with accuracy and reaction time recorded. For the visual and the verbal task the positions of the buttons were selected randomly for each participant. Prior to the baseline the participants trained the secondary task for several minutes.

Wayfinding phase. In the wayfinding phase participants had to walk the two routes by using a joystick to control for heading and forward translation speed. The maximal translation speed was two meters per second. In order to reduce simulator sickness the participants were not able to rotate faster than 30° per second. All relevant parameters were recorded with approximately 100 Hz in order to compute (1) the time from the first movement to reach the goal, (2) the traversed distance, (3) the number of stops and (4) the number incidents when participants got lost. Stops were counted if they at least lasted one second and started at least one second after a previous stop. A participant was considered to be lost when turning into a wrong street for about five meters. In this case the participant was stopped by the simulation and had to turn around in order to continue the navigation. From these four parameters we considered "getting lost" as the most important. Distance and getting lost correlated by .89 ($n = 24$, $p < .001$). So both measures almost showed identical results and therefore only getting lost, stops and time are reported.

Prior to the experiment, the participants were familiarized with the virtual reality setting and the joystick in a small area of Virtual Tübingen not encountered during the rest of the experiment.

3 Results

For the statistical analysis values deviating more than three standard deviations from the overall mean were replaced by the most extreme value inside this interval. For group differences one-way ANOVAS for performance over both routes were computed followed by planned contrasts between the experimental groups.[1]

3.1 Wayfinding Performance

There was a main effect of secondary tasks in the frequency of getting lost (see Figure 4, ANOVA $F(3, 20) = 5.43$, $p = .007$; $\eta^2 = 0.45$). The planned single contrasts show that the spatial secondary task influenced the encoding of environmental information used for wayfinding compared to the control group ($t(20) = 3.05$, $p = .006$, $d = 0.62$). Also the verbal secondary task had an influence ($t(20) = 3.78$, $p = .001$, $d = 0.77$). The visual secondary task had no general significant influence compared to the control group ($t(20) = 1.89$, $p = .074$, $d = 0.39$).

We also compared the groups performing a secondary task with each other (although these tests are not orthogonal). As seen in Figure 4 the verbal secondary task had a bigger influence than the visual secondary task. This difference attained significance on the short route ($t(20) = 2.55$, $p = .019$, $d = 0.52$), but not on the long route ($t(20) = 0.59$, $p = .571$, $d = 0.12$). From visual inspection the spatial secondary task had a bigger influence than the visual secondary task. This effect nearly attained statistic significance on the short route ($t(20) = 2.03$, $p = .056$, $d = 0.41$; long route: $t(20) = 0.20$, $p = .840$, $d = 0.041$). We found no differences between participants with a spatial and a verbal secondary task ($t(20) = 0.73$, $p = .476$, $d = 0.15$). The histograms in Figure 6 show that the results were not due to single individuals. There were no effects for time ($F(3, 20) = 2.21$, $p = .118$; $\eta^2 = .25$) and stops ($F(3, 20) = 0.80$, $p = .510$; $\eta^2 = .11$) which excludes a speed accuracy trade-off as an explanation for our results.

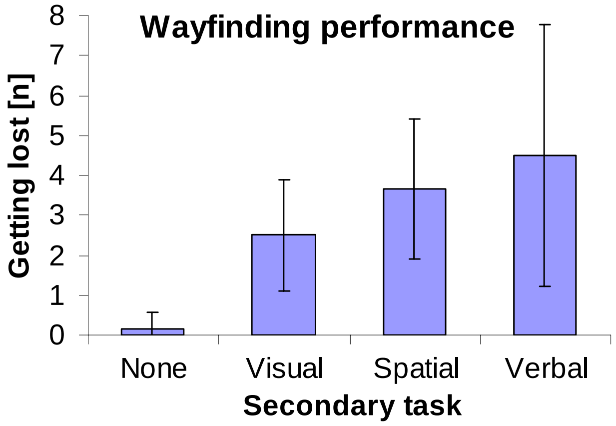

Figure 4: Getting lost per person on both routes as a function of the secondary task during encoding. Means and standard deviations are shown.

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[1] No differences for the order of route presentation could be found (time: $t(22) = 0.18$, $p = .863$, $d = 0.037$; got lost: $t(22) = 0.32$, $p = .752$, $d = 0.065$; stops: $t(16.7) = 0.46$, $p = .654$, $d = 0.094$). The data was collapsed across both orders for the further analysis.

3.2 Secondary Task Performance

To rule out the explanation that differences in the main tasks are only due to differences in the secondary tasks we analyzed the secondary tasks. Overall, the three groups with secondary tasks did not differ in accuracy on the baseline taken before the main experiment (see left hand side of Figure 5; $F(2, 15) = 1.68$, $p = .220$; $\eta^2 = 0.18$). As in the pre-tests the secondary tasks were comparable with regard to their difficulty.

There was also no main effect of secondary task during encoding (see right hand side of Figure 5; $F(2, 15) = 3.12$, $p = .074$, $\eta^2 = 0.29$). First and secondary task did not correlate ($n = 18$, $r = -.24$, $p = .342$). No trade-off between main and secondary task, therefore, could explain the results. The direction of the contrasts even point into the same direction as in wayfinding performance: The accuracy in the visual task was higher compared to the spatial task ($t(15) = 2.45$, $p = .027$, $d = 0.58$). The accuracy in the visual task compared to the verbal task showed the same pattern of results, but did not reach significance ($t(15) = 1.66$, $p = .118$, $d = 0.39$). No differences between the spatial and the verbal task were found ($t(15) = 0.79$, $p = .444$, $d = 0.19$).

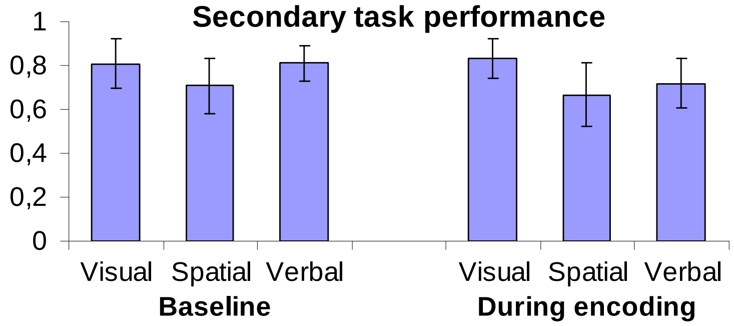

Figure 5: Accuracy in the secondary tasks during baseline (left) and during encoding of the routes the participants had to walk immediately afterwards (right).

Performance in the secondary task depended on the distance to a decision point (i.e., an intersection). These differences were found for accuracy scores in the verbal secondary task condition (Figure 7; overall differences $F(22, 330) = 2.18$, $p = .002$, $\eta^2 = .13$), whereas these differences were not found for the other two secondary task conditions (verbal secondary task: $F(22, 110) = 1.99$, $p = .011$, $\eta^2 = .28$; visual secondary task: $F(22, 110) = 1.37$, $p = .149$, $\eta^2 = .21$; spatial secondary task: $F(22, 110) = 1.24$, $p = .230$, $\eta^2 = .20$). Overall, the interaction between secondary task and distance to an intersection was not significant ($F(44, 330) = 1.16$, $p = .233$, $\eta^2 = .13$). Also no effect was found for secondary task presentation time as function of temporal distance to an intersection (visual secondary task: $F(20, 100) = 1.02$, $p = .447$, $\eta^2 = .17$; spatial secondary task: $F(22, 110) = 0.59$, $p = .925$, $\eta^2 = .11$; verbal secondary task: $F(22, 110) = 1.0$, $p = .476$, $\eta^2 = .17$; see Figure 8). The accuracy and the presentation time of a secondary task also did not correlate with each other excluding a speed-accuracy tradeoff in the secondary tasks (see Figure 9).

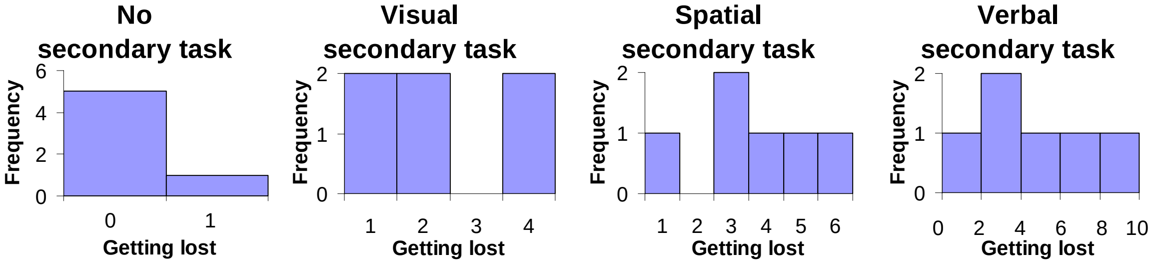

Figure 6: Histograms for the number of occasions in which each participant got lost during the four conditions.

4 Discussion

The present study examined the working memory systems relevant for wayfinding. A verbal task put additional load on the PL. A visual and a spatial secondary task were used to put additional load on the VSSP, and to distinguish between the visual and spatial components of this subsystem. The main finding is that the verbal and the spatial secondary task interfered with wayfinding performance. First, they interfered compared to a control group. In contrast, the visual secondary tasks only had mild effects on wayfinding performance. Second, the verbal and the spatial secondary task also interfered stronger than the visual secondary task.

Our findings indicate that both the PL and the VSSP in Baddeley's working memory theory are involved in the encoding of environmental information used for wayfinding. The involvement of the PL indicates a kind of "verbal encoding" which might take the form of verbal directions like "left, then right, next left, straight, left …" (cf. Couclelis, 1996; Daniel & Denis, 2004; Denis, 1997; Denis et al., 1999, Lovelace et al., 1999). In our experiment, producing such directions was inhibited by the verbal secondary task leading to worse performance during wayfinding. This interpretation is also supported by a questionnaire that had to be answered after the experiment. In this questionnaire the verbal strategy of rehearsing route directions correlated highest with good wayfinding performance (r around .50).

The VSSP was also involved in wayfinding. However, it is a novel finding that an effect was found for the spatial, but not for the visual secondary task (cf. Garden, Cornoldi, & Logie, 2002). Participants with the visual secondary task performed better than participants with the spatial secondary task. The spatial component of the VSSP seemed to be more important than the visual one. This points towards a higher importance for abstract spatial features like the geometry of an environment compared to mere visual surface features as proposed by Cheng (1986) and Gallistel (1990, see also Hermer & Spelke, 1994; Hermer-Vasquez, Spelke & Katnelson, 1999; Learmonth, Nadel & Newcombe, 2002; Wang & Spelke, 2002 discussed in more detail below). It also points against heavy reliance on

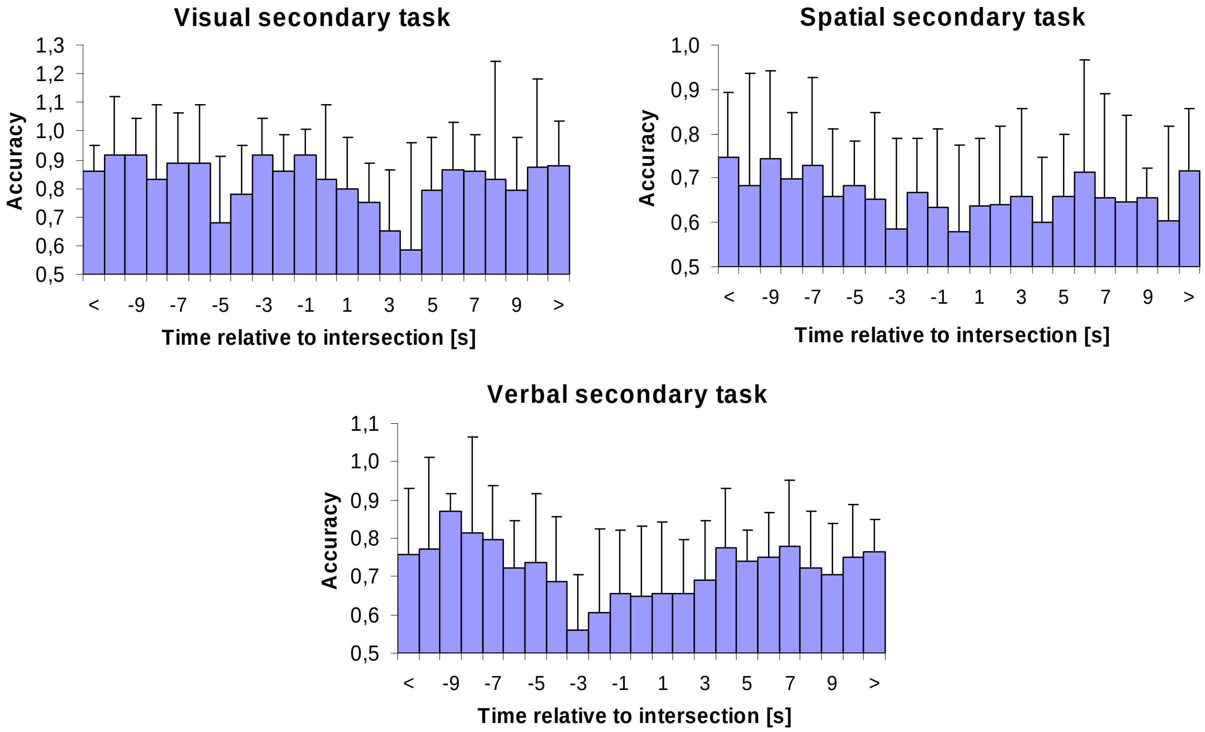

Figure 7: Accuracy in the secondary tasks as a function of time relative to passing the middle of an intersection.

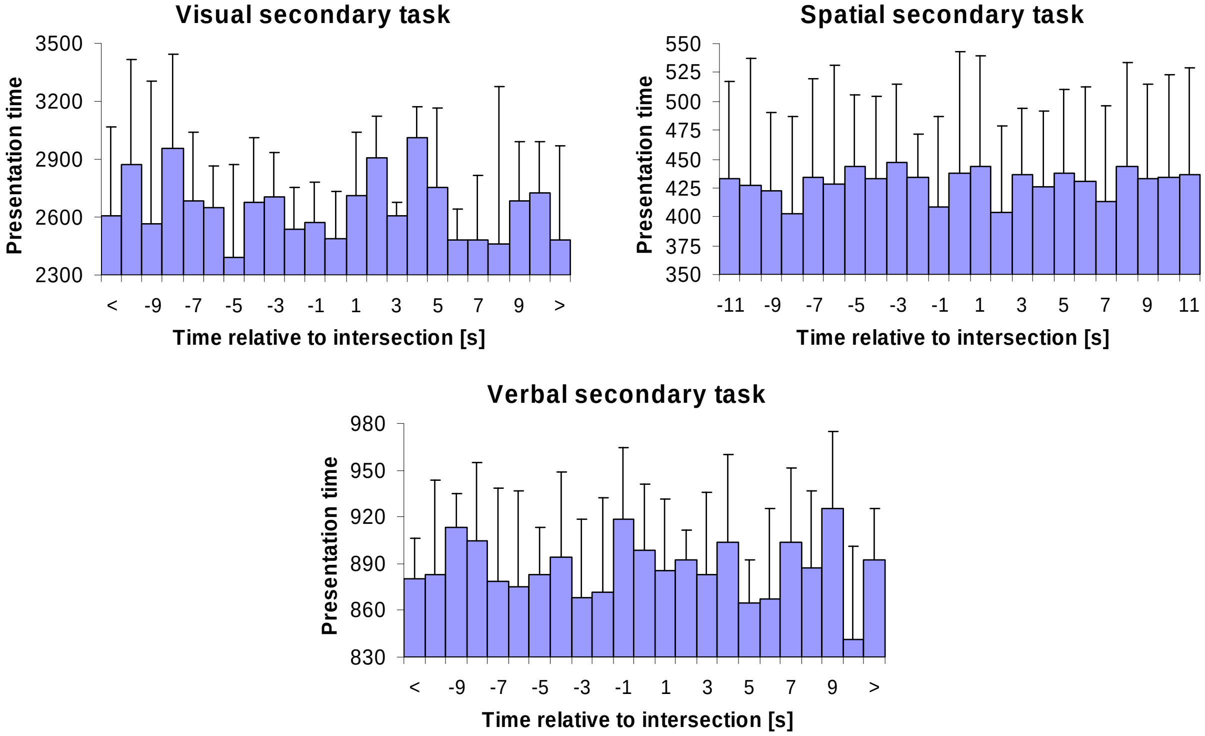

Figure 8: Presentation time of the secondary tasks as a function of time relative to passing the middle of an intersection.

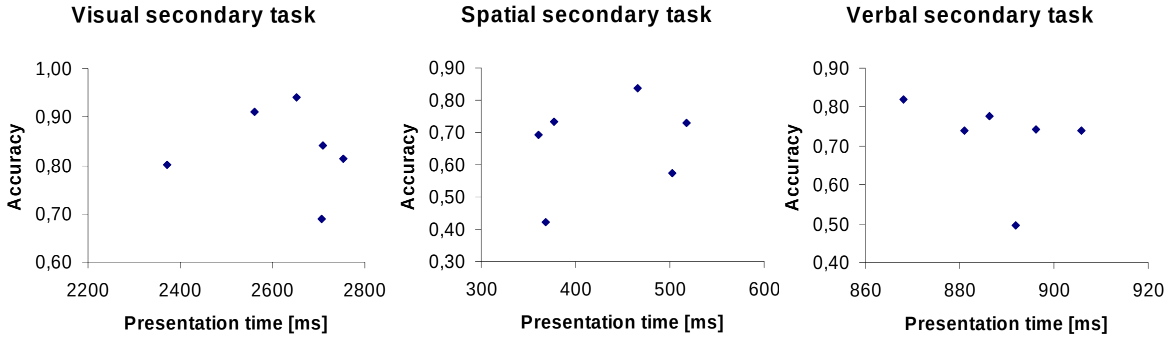

Figure 9: Accuracy as a function of presentation time per participant for the three conditions with secondary tasks.

pictorial information in form of snapshots of the environment (Mallot & Gillner, 2000) or in form of a map as seen from birds eye view (e.g., Kosslyn et al., 1978).

Is there an alternative interpretation of our findings? One might argue that the visual task required imagination whereas the verbal and the spatial tasks were more perceptual in nature. Are our differences due to the fact that the visual secondary task was cognitively more demanding (i.e., requiring deeper, more complex and more time consuming processing)? We do not think that is a plausible explanation. If the visual secondary task required a deeper processing, it should have also interfered more strongly with the deeper processing of wayfinding information. Usually deeper processing is associated with better memory performance (e.g. Craik & Tulving, 1975). However, a stronger interference with deeper processing should lead to worse memory performance compared to other tasks and not to better performance as was observed in learning while performing the visual secondary task.

Another possible interpretation is that the three secondary tasks did not load a single subsystem each, but rather had different visual, spatial, and verbal components. For instance, not only the spatial secondary task entailed spatial components. The visual secondary task also contained spatial aspects, i.e., the participants had to imagine a clock including watch hands which pointed into a specific direction and they divided the imagined clock into an upper half and a lower half. Moreover, pressing buttons on a response box includes a spatial component, as either the left or the right button has to be pressed. The verbal task had the same problem. However, we do not think that these considerations present problems for our interpretations. First, the problem that a certain secondary tasks does not only put load only on the intended working memory subsystem, but also on other (unintended) subsystems, is a very general problem of the secondary task paradigm. All experiments in the paradigm have to deal with this problem (Gopher & Donchin, 1986). The visual secondary task might not load on an isolated system, but we think that it put much more load on the intended than on the unintended subsystem. In our experiment, we used secondary tasks that are very similar the "standard tasks" of working memory research (e.g., Baddeley, 1986; Logie, 1995). A second support for our interpretation comes from earlier studies on human wayfinding. These studies also showed that environmental information is not encoded in one single memory system, i.e., representational format and that wayfinders rely on spatial and verbal memory subsystems (Garden et al., 2002; Meilinger & Knauff, submitted; Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000).

We believe that the most plausible interpretation of our findings is that wayfinding knowledge is not represented in a single format, but rather in two different but strongly interconnected formats. The root of this idea is in the innovative work by Paivio and collaborators (e.g., Paivio, 1971). In the following we propose a dual-coding theory of human wayfinding knowledge that is inspired by Paivio's theory (Paivio, 1971; 1986; 1991).

The dual-coding theory of human wayfinding knowledge we are suggesting relies on the assumption that environmental information is encoded not only in a spatial format, but also in a verbal format. Our data suggest that during learning, the environmental information is encoded into a spatial format and additionally re-coded into verbal directions like "2nd right". If an item must be retrieved from memory it can directly activate a verbal or a spatial representation. However, the retrieval can also trigger references between the systems; the activation of a verbal memory trace can cross-activate an entity in the spatial system and vice-versa. The account is supported by many findings. In wayfinding Garden et al. (2002) found similar performance levels in participants who learned and retraced a route either during a spatial tapping or a verbal shadowing task. As in the present study, the dual coding approach predicts encoding this route in a spatial and a verbal format. Equal interference levels are therefore expected. In wayfinding with maps and verbal directions several studies found similar wayfinding performance for both wayfinding aids (Meilinger & Knauff, submitted; Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000). According to the dual-coding approach the participants additionally encoded the map in a verbal format that is verbal directions. If they also focused on these verbal directions, the similar performance levels for map instruction and verbal directions can be explained.

Paivio's original claim of dual coding was mainly about encoding verbally presented information in an additional visuospatial format. In the context of wayfinding however, dual coding is the other way round. It is about encoding spatial information additionally in a verbal format. This relates to embodiment and to the grounding problem of how knowledge is connected to the world from which it is acquired and how it is then used in order to act. A spatial representation acquired while navigating through the world or at least watching a video of a highly realistic city is probably well grounded. It is closely related to our perceptual input and probably can be used by an embodied agent for retracing a route without translating it into a more abstract propositional format and without having to rely on complex higher-level cognitive processes. Most non-human animals are thought to navigate on this level. The dual coding theory proposes that we additionally recode this spatial format into a verbal format. This involves further abstraction from the perceptual input. However, the spatial representation might also in a sense ground the verbal representation at a higher level.

A related account is the perceptual symbol system approach by Barsalou (e.g, Barsalou, 1999; Barsalou, Simmons, Barbey & Wilson, 2003). In this approach a modality specific conceptual system is assumed. However, such perceptual symbols alone do not seem to be sufficient to explain the results in our experiment, because the verbal secondary task had a disrupting effect on wayfinding performance and this indicates that a "non-perceptual", language-based or propositional format may also be involved in human wayfinding (see also Garden et al., 2002; Hermer-Vasquez et al., 1999).

On a more general level, the combination of spatial and verbal encoding can also be found in other cognitive theories (e.g., Huttenlocher, Hedges & Duncan, 1991; Kosslyn et al., 1989; Creem & Profit, 1998). These approaches typically differentiate between a categorical and a precise, more perception based format. This latter format is always assumed to be more fine-grained than the categorical. It could be spatial in general (Huttenlocher et al., 1991), based on a coordinate system (Kosslyn et al., 1989) or linked to action (Creem & Profit, 1998; cf., Goodale & Milner, 1992). The categorical system often remains rather unspecified. We would like to complement these theories by proposing that storing spatial information categorically often works simply by storing verbal descriptions like, "at the T-intersection" or "turn right" etc. Encoding spatial information verbally in this way can account for many biases found in spatial memory. For example, it may account for biases in the memory of locations (Fitting, Allen & Wedell, in press; Huttenlocher et al., 1991), biases in the angles of intersections (e.g., Tversky, 1981) and it may mediate grouping effects due to political, semantic or conceptual similarities (e.g., Carbon & Leder, 2005; Hirtle & Mascolo, 1986).

The dual coding theory is mainly concerned with memory, predicting better performance by using multiple memory systems and explaining biases due to categorical encoding. However, by representing spatial information verbally, this verbal representation is accessible again as an input to our reasoning (Clark, 2006). This allows for new ways to acquire conclusions about our spatial environment. For example when turning right twice in a grid city, wayfinders might conclude that they are now walking back in the direction that they were coming from and therefore assumed that they went the wrong way. They could come to that conclusion also based exclusively on their spatial or fine-grained representation (e.g., mentally simulating their former path while updating their original orientation). However, with verbal representations they gain multiple options for reasoning which allows for much more flexibility as well as individual preferences in strategy choice.

The dual coding approach assumes additional verbal encoding of spatial information. Our findings also provide as preliminary indication of when this might happen during the learning of the route. In accordance with studies indicating the relevance of decision points for wayfinding (e.g., Aginsky, Harris, Rensink & Beusmans, 1997; Janzen, 2006) in our experiment the accuracy in the verbal secondary task decreased when the participants were approaching an intersection. Apparently, the interference was strongest not in the middle of an intersection, but rather shortly before the participants were reaching a decision point. This might be the moment at which spatial and verbal information processing overlap. However, additional research is needed to find further evidence to support this idea.

The dual-coding approach can also provide an alternative interpretation for the empirical findings in reorientation experiments. In the reorientation literature, geometry is considered an important component (cf. Wang & Spelke, 2002). This notion supports the interpretation of the spatial component in our experiment as geometry. The debate in reorientation research, however, mainly focused on the question of whether language processes were necessary to combine geometric and feature information – in our terms spatial and visual information - as proposed by Hermer-Vasquez et al. (1999; see also Wang & Spelke, 2002). For example, they showed that adults generally use both geometric and feature information unless they are disturbed by a verbal shadowing task where they have to immediately repeat words from a text presented via headphones. This interference does not occur during clapping a rhythm or repeating syllables. The assumption that language is necessary for combining geometric and feature information, however, is questioned by the finding that primates, birds and even fish are able to accomplish this (e.g., Gouteux, Thinus-Blanc & Vauclair, 2001; Sovrano, Bisazza & Vallortigara, 2002). Also, the shadowing effects of language do not occur when the adults receive a training trial and more explicit instructions (Ratkliff & Newcombe, 2005). Our dual-coding approach assumes spatial (geometric) and visual (feature) information to be additionally coded in verbal format. It can explain the usefulness of language, without assuming language to be necessary for reorientation. It also explains the boost in reorientation performance within children around the ages of five and six years regarding their emerging spatial language abilities, e.g., verbal expressions involving the terms “left” and “right” (Hermer-Vazquez, Moffett & Munkholm, 2001; Learmonth et al., 2002). As mentioned such emerging verbal representations may be a new basis for childrens’ reasoning about space and are grounded in corresponding visual or spatial representations.

A possible disadvantage of our study is that our participants were placed in a virtual environment and also “walked” virtually, not physically. Various spatial orientation experiments have shown the importance of bodily cues available during walking (i.e., vestibular information especially during turns, proprioceptive information and efference copies; Gale, Golledge, Pellegrino & Doherty, 1990; Klatzky, Loomis, Beall, Chance & Golledge, 1998; but see also Riecke, van Veen & Bülthoff, 2002). In our experiment participants could not use these cues, but had to rely explicitly on the simulation. It is possible that this is one reason that spatial and verbal memory systems were found to be more important than visual memory. We cannot rule out this criticism. However, this critique would apply to most experiments that use a virtual environment paradigm to merge high variable control and maximally realistic experimental conditions.

As Baddeley (2003) pointed out, little work has been done on the role of the VSSP in spatial orientation. This experiment is a small step towards changing this situation. On the one side, our results point towards a further differentiation of the VSSP into spatial and visual subsystems in the context of spatial orientation, with the spatial subsystem being involved more strongly. On the other side, our results highlight the involvement of the PL for spatial orientation. Although PL and VSSP might have developed for different demands posed from our environment, we seem to leverage both of them in order to solve our tasks in experimental situations as well as in daily life.

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3.2 Ask for directions or use a map

Ask for directions or use a map: A field experiment on spatial orientation and wayfinding in an urban environment

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Abstract: When planning a route we usually study a map, ask other people for verbal directions, or use a route planner. Which source of information is most helpful? This experiment investigated human wayfinding and knowledge acquisition in urban environments. Participants were required to retrace two different routes learned either from route maps, or from verbal directions. We show that both maps and verbal directions are equally useful tools for conveying wayfinding knowledge. Even the survey knowledge of map-learners was not better. We argue that both verbal directions and maps are memorized in a language-based format, which is mainly used for wayfinding.

Keywords: wayfinding – map – verbal directions – route knowledge – survey knowledge – field experiment

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1 Introduction

Imagine walking through a foreign city. The crowd carries you until it starts getting dark. Then you are planning to go back to the hotel and you immediately notice that you do not remember at all which way you came. You are lost! There are basically two possibilities to find the way back to your hotel: by asking somebody for the way or by using a map. But which is better? The goal of the present study is to answer this question and at the same time to explore how wayfinding knowledge is represented in human memory.

The starting point of our study was that the acquisition and representation of wayfinding knowledge is usually studied either by the direct experience of the actual environment or it is studied by learning from maps or texts (e.g. Moeser, 1988; Richardson, Montello & Hegarty, 1999; Taylor & Tversky, 1992; Thorndyke & Hayes-Roth, 1982). In such studies, the individuals navigate through a real or virtual environment and then different performance measures are analysed. In daily life, however, before we start our journey we usually plan the route by studying a map, asking other people, or – more recently – use a route planner, for instance, from the web. What happens if individuals acquire their initial knowledge from such "indirect" sources of information and then have to find their way through the real environment? Which source of information is more helpful when finding our way? And if one of the information sources is considered to be more helpful, does that apply to all sorts of routes?

In the following, we report a field-experiment in an urban environment in which participants learned two different routes, either from route maps, or from verbal directions, before walking a route. In a number of post-tests, we then investigated how the routes were represented in memory. Here we refer to the distinction between route knowledge and survey knowledge. Route knowledge describes the path that one must walk to reach the goal by telling the individual what to do at the decision points on the route, e.g. turn right at the church, then the second street to the left. It is one-dimensional or "string-like" and it does not necessarily involve the knowledge of the exact location of the goal. Survey knowledge, on the other hand, tells you in which direction and distance a location is to be found independent from knowing a path which leads you there, e.g. the train station is about 300 Meters east from here. It is two-dimensional or "map-like". (e.g. Golledge, 1990, 1999; Herrmann, Schweizer, Janzen & Katz, 1998; Kitchin and Freundschuh, 2000; Montello, Waller, Hegarty & Richardson, 2004; Siegel & White, 1975). We discuss our results in relation to other accounts of human wayfinding and draw some general conclusions about wayfinding, verbal directions, maps, and the representation of wayfinding knowledge in memory.

2 Method

2.1 Participants

The experiment took place in Tübingen and the participants were recruited in Freiburg. The cities are about 200 kilometres away from each other. To ensure participants had never been to Tübingen before, we presented 35 volunteers with a list of four cities in the south of Germany. They had to mark all cities to which they had been before. From this sample we selected twelve participants who never had been to Tübingen before. Half of the participants were female and half were male. They were students from the University of Freiburg between 20 and 31 (M = 24; SD = 3.3). They all were German native speakers and they were paid €50 for their participation. They were transported by bus, from Freiburg to Tübingen, on the morning of the study and were taken back to Freiburg in the evening.

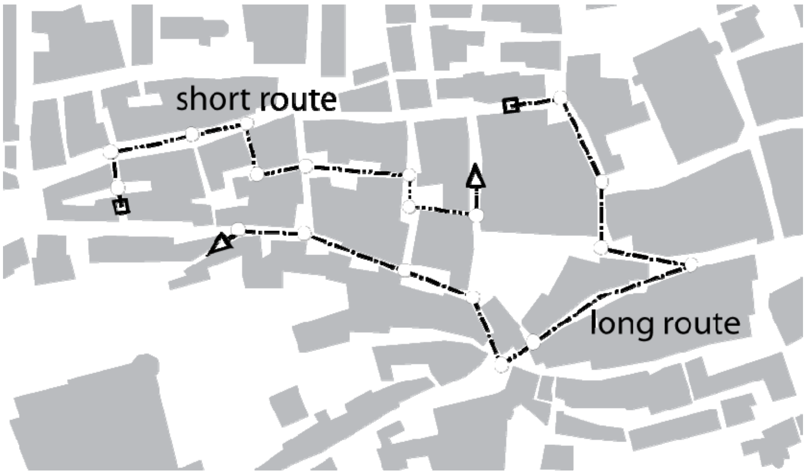
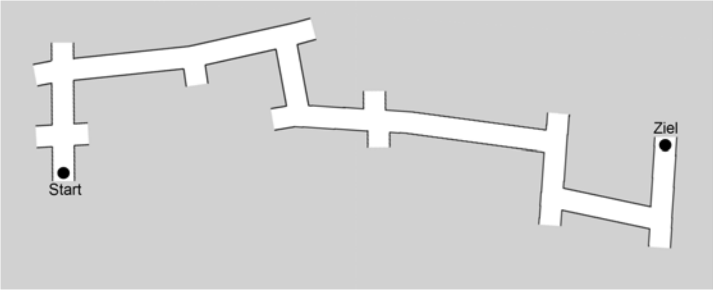


Figure 1: A map of the area the experiment took place and the two routes. Circles correspond to intersections.

2.2 Material and Design

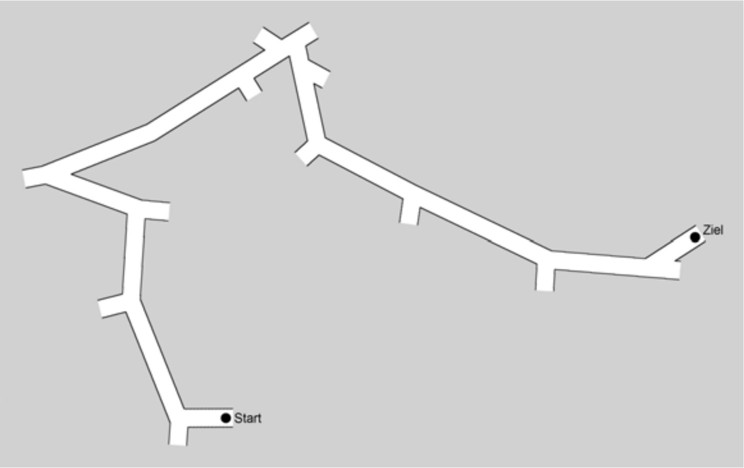
A map of the city centre of Tübingen in which the experiment took place is presented in Figure 1. We systematically varied route length (short vs. long) and source of information (map vs. directions). The short route was 320 metres long and had 9 almost orthogonal intersections with 21 alternatives. The long route was 480 metres long had 10 intersections, 23 alternatives and most intersections were at oblique angles.

In the map-condition, the participants received a route map that a professional geographer constructed on the basis of official maps (see Figure 2). This route map exclusively communicated the topographically correct layout of this specific route without other geographical (e.g. house corners) or further features (e.g. landmarks, street names, surrounding environment). Accordingly, all streets on the maps were drawn with the same width. In this way the information provided by the map was maximally concordant with the information from the verbal directions. The size of the paper sheet with the map was A4. In the directions-condition, participants received the instructions as written sentences on a paper of the same size. Again our goal was to provide the same information with the direction and the maps. Thus, the sentential directions were determined in a pilot study following the "skeletal description" introduced by Denis (1997). A different sample of six female and six male volunteers generated verbal directions based on the maps. The persons were not familiar with Tübingen. These verbal directions were recorded and typed on paper. Descriptions were analysed for how often features were mentioned. If a feature was mentioned by the majority of the participants then this was used in the directions. This criterion was agreed on by two independent raters. To ensure unambiguousness three further features also mentioned in the descriptions were added on the long route (e.g. turn "sharp" right). Two examples of an original direction are presented in the Appendix. The maps for the short and the long route and the corresponding directions are shown in Figure 2a and Figure 2b, respectively.



Go straight on.
Turn right at the 2nd intersection.
Turn right again at the 2nd intersection.
Then left.
Then the 2nd to the right.
Turn left the 1st.
Left again.
Here is your goal.

Figure 2a: The map of the short route and the corresponding verbal directions translated into English.



Go straight on.
Take the first right.
Straight on until it is not possible to do so any more.
Then turn left.
Then turn sharp right at the next opportunity.
Go straight on.
There is a crossroad to the right.
Do not take this one, but the 2nd intersection sharp right.
Go straight on and turn half left.
Go straight past 2 streets on the right.
On the 1st intersection turn half left.
Here is your goal.

Figure 2b: The map of the long route and the corresponding verbal directions translated into English.

2.3 Procedure

The experiment followed a mixed 2 (routes) x 2 (group) design. Half of the participants got the map on the short route and the directions on the long route. The other half of participants got the map on the long route and the directions on the short. This particular design was chosen to provide higher power in the direct comparison between map and directions as this is a within subjects comparison in our design. The order of routes was controlled. However, due to the number of participants and the mixed design, no interactions between order and the other factors could be analyzed.

Each participant was tested individually. They waited for the experiment in a university room, were escorted to one of the starting points blindfolded, and then turned around to minimize prior orientation. Then the participants were given three minutes to study the maps or the verbal descriptions. After the three minutes they had to answer a control question. If they were not able to answer this question they had two additional minutes study time. It is important to notice that the maps or the directions were taken away after the study phase so that the participants had to keep in mind and to maintain the acquired information in memory. Then the participants were requested to walk from the start to the destination point (see Figure 2). The performance measures were recorded by the experimenter or one of the two assistants. The recorder followed the participant with a distance of about five metres and recorded:

1. the time to reach the goal,
2. the number of stops,
3. how often the participant got lost, i.e. entered a wrong street for five meters, and
4. how often the participant asked the experimenter for help (the participants were not allowed to ask other people on the street)

Contrary to prior briefing the help was offered to the participants, but just after a participant was lost or stopped for 30 seconds. When the participants had reached the goal they were blindfolded again and then taken to the second starting point. Here the same procedure was used. To avoid learning- or ordering effects, the order of conditions and routes was counterbalanced, as were the experimenters and the gender of the participants. A snapshot of one experimental situation is presented in Figure 3.

Figure 3: A participant walking the route followed by an experimenter recording the dependent measures.

After the main experiment, the participants were asked to perform a series of post-tests. First, a set of tests was used to measure whether the participants had acquired survey knowledge. A second set to measure their route knowledge. At last, they filled in a questionnaire about the strategies they applied to solve the navigation tasks e.g. “During memorising the map, did you memorise it as directions e.g. ‘the 2nd street to the right’?” or “Did you try to walk directly in the direction the goal or a subgoal?”

To measure *survey knowledge* three different tests were conducted. In a pointing task, the participants stood at the goal. Here they were asked to point with the index finger in the direction of the starting point and mention an object in this direction e.g. the left end of the 2nd window. The experimenter marked the direction in a 360° picture (see Figure 4) and then the angle between where the participants pointed to and the target location was calculated.

The distance estimation task also was conducted at the goal. The participants were asked to mark the straight-line distance to the starting point on a visual analogues scale (see Figure 4).

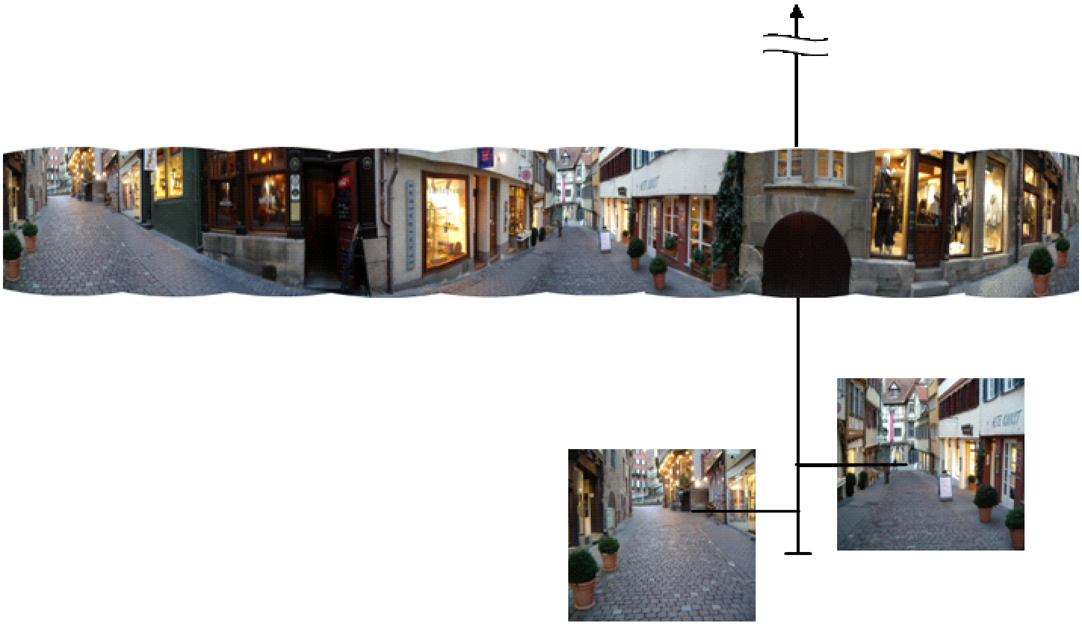


Figure 4: Material used for the pointing task to measure survey knowledge from a horizontal perspective. In front the 360fl-picture was used for marking the direction of the start from the goal. In the background the scale was used for estimating the straight-line distance of the start with two visible anchors.

In order to get an idea of distances on the scale two anchor distances were indicated. The anchors were two objects in the visible environment e.g. a corner of a house. This anchor was marked on a photograph and the corresponding distance indicated on the scale. So the participants saw the distance to this corner of the house and they could see how this related to the distance marked on the scale. Two objects in opposite directions from the goal point at distances of 22 and 48 metres were used for each of the two routes.

In a marking task, the participants were back in the waiting room and had to mark the starting points of a route on a map only showing the goal area of the route (see Figure 5). From this, first, the angle between the direction where the participants marked the starting point and the actual direction of the starting was calculated. Second, the marked distance between start and goal point was measured and compared to the correct distance.

Figure 5: The goal areas of the short (left) and long route (right) the participants used to mark the start points.

To measure *route knowledge* two different tasks were used.

In a drawing task, the participants had to draw the routes. This was done after marking the start point in a map of the goal region. The participants had to draw the missing route and the drawn turning points were counted. The number of deviations from the six required turns was counted as errors.

Additionally the participants were asked to give verbal directions. Like in the drawing task errors in number of turns mentioned were taken as the dependent variable.

3 Results

3.1 Wayfinding performance

The findings reported in this section are mainly based on nonparametric statistical tests. Such tests are appropriate for assessing the significance of differences in data when the assumptions of normal distribution and homogeneity of variances are violated (Siegel & Castellan, 1988). For statistical decisions, an alpha level of .05 was adopted.

The performance of the participants as a function of route length is presented in Table 1. On the long route the participants walked longer (Wilcoxon Test, $Z = 3.06$, $p = .002$), made more stops ($Z = 2.99$, $p = .003$) got lost more often ($Z = 2.17$, $p = .030$) and needed further instructions more often ($Z = 2.12$, $p = .034$).

	Short route		*Long route*	
	M	*SD*	*M*	*SD*
Time [min]	3	0.5	6.5	0.9
Stops	0.3	0.5	1.8	1
Got lost	0.6	0.9	1.3	1
Needed instructions	0.1	0.3	0.6	0.7

Table 1: Wayfinding performance on the short and the long route

The performance as a function of map-learning and direction-learning is presented in Table 2. The data show that under both conditions the performance was almost identical. Map-learners and direction-learners needed about the same time to walk the two routes ($Z = 0.78$, $p = .433$), they stopped equally often ($Z = 0.59$, $p = .555$), they got lost equally often ($Z = 0.29$, $p = .773$) and they asked the experimenter for help equally often ($Z = 0.0$, $p = 1$). The performance with maps and directions was not significantly different on the two routes (four U-tests on two routes; all eight $Z < 1.64$, $p > .10$).

	Map		*Directions*	
	M	*SD*	*M*	*SD*
Time [min]	5.3	1.8	4.9	1.6
Stops	1.3	1.4	0.9	0.8
Got lost	0.9	1,1	1	1
Needed instructions	0.3	0.7	0.3	0.5

Table 2: Wayfinding performance for map and verbal directions

3.2 Route and survey knowledge

In the post test the variability in direction estimation was compared with F-Tests. Values deviating more than two standard deviations from the overall mean were replaced by the most extreme value within two standard deviations. The rest of the data were analysed with nonparametric tests.

The pointing task, the distance estimation task, and the marking task, measured survey knowledge.

Pointing task. Participants with maps and verbal directions did not differ in their performance of pointing from the goal to the start (see Table 3; systematic error expressed by mean deviations: U-Test short route: $Z = 0.481$, $p = .630$; long route $Z = 1.04$, $p = .296$; unsystematic error expressed by standard deviations: $F(11, 11) = 1.02$, $p > .25$).

Distance estimation task. There was also no difference in the distance errors between map-learners and direction-learners (see Table 3; deviation of estimated distance to correct distance. U-Test short route $Z = 0.641$, $p = .522$; long route $Z = 0.641$, $p = .522$).

Marking task. Map-learners were more accurate in estimating the direction of the starting point which is shown by their lower standard deviation, a measure for the unsystematic error (see Table 3; $F(11, 11) = 3.80$, $p < 0.05$). There was no difference in the systematic error expressed by mean deviations (U-Test short route $Z = 1.20$, $p = .229$; long route $Z = 1.69$, $p = .091$). Map-learners overestimated the distance (Binomial Test: 2 underestimations vs. 10 overestimations $p = .039$) which was not the case in direction-learners (Binomial Test: 5 underestimations vs. 7 overestimations $p = .774$).

Route knowledge was measured in a drawing task and in giving directions.

Drawing task. There was no main effect of route length on errors in drawing turns ($\chi^2(1, N = 17) = 2.88$, $p = .089$), and no difference between map-learners and direction-learners (see Table 4; $\chi^2(1, N = 17) = 0.059$, $p = .808$). No interaction was revealed ($\chi^2(1, N = 17) = 0.142$, $p = .707$).

	Map		*Directions*	
	M	*SD*	*M*	*SD*
Pointing and distance estimation				
Direction error [fl]	12	35	13	48
Distance error [m]	76	81	76	78
Marking task				
Direction error [fl]	15	20	5	49
Distance error [m]	48	57	-4	64

Table 3: Errors in pointing, direction estimation and marking. For pointing and distance estimation the participants stood at the goal point. For the marking task the participants marked the start point in a map which displayed the goal area. Positive numbers indicate pointing to the left in direction error and an overestimation in distance error.

Giving directions. The participants were very precise in giving directions. In number of required turns just seven errors were committed altogether (see Table 4). Due to the small number, the errors were not analysed further with regard to source of information or route. Comparing them to the drawing task the participants made less errors in giving verbal directions compared to drawing a route with respect to necessary intersections to turn at ($\chi^2(1, N = 24) = 4.17$, $p = .041$).

3.3 Questionnaire

Although asking participants for their strategies has severe limitations, it can provide some clues as to how the participants used the maps and directions in navigation (or at least think that they did). Two aspects were important here: First, all participants reported having translated the map into directions during memorising the map. Second, when using the map three participants reported orienting on the direction they assumed the goal or a subgoal was and trying to walk in this direction rather than orientating on the course of the route. The latter navigation strategy was correlated with bad performance: participants got lost more often ($N = 12$; $r = .84$, $p = .001$) and needed the instructions more often ($N = 12$; $r = .78$, $p = .003$).

	Map	*Directions*	*Sum*
Drawing Turns	9	8	17
Giving Directions	5	2	7

Table 4: Errors in Drawing Turns and in Mentioning Turns when Giving Directions

4 Discussion

We conducted a field experiment on human navigation under highly realistic conditions. Our starting point was that in many related studies the acquisition and representation of spatial knowledge has been studied via direct experience of an environment. Still, in daily life we, first, ask someone for directions, search for an appropriate route in a map or more recently look for route-maps and directions in the WWW. So the knowledge we acquire by that, originates from the "indirect" instructions and from the "direct" experience of the environment. The present study was designed to resemble this "natural" wayfinding situation. The most important finding was that maps and verbal directions seem to be equally useful tools for conveying wayfinding knowledge. There was no main effect of the source of information. Many theorists would have predicted such a difference because there might be a general advantage for depictions (Larkin & Simon, 1987; Freksa, 1999; Paivio 1971, 1986). The obvious explanation is that the null-difference is simply due to the small sample size. In fact, for the effect sizes observed in our experiment we would have needed more than ten times as many participants to obtain significant results in an independent t-test, for getting lost even more than 100 times as many. We do not think that the lack of power explains our nulleffect.

In fact, our finding is in accordance with other studies which also did not find a difference between maps and directions in terms of time and errors (Schlender, Peters & Wienhöfer, 2000; Pazzaglia & De Beni, 2001). According to Schlender et al. (2000) equal performance levels indicate that wayfinders waive the advantages of a map by mentally rotating the map to align it with the environment that is ensuring that "up" in the map matches "forward" in the environment (e.g. Klippel, Freksa, & Winter, 2006; Levine, Jankovic, & Hanley, 1982, Rossano & Warren, 1989). Another possible reason is that depictions force the participants to store spatial information that might be irrelevant if they reach the corresponding location during navigation. As Bishop Berkeley long ago noted, one can only depict a particular triangle, with specific angles and sides, not a general, abstract triangle (quoted in Tversky, Lee & Mainwaring, 1999). The need of maintaining all spatial relations from the map in memory might waste cognitive resources and, thus, waive advantages of maps. Verbal directions, in contrast, are certainly useful, but their convenience highly depends on their quality. As everybody knows some verbal directions are not helpful at all. However, in our study we used the method of "skeletal description" to generate an optimal description of the route. In several publications, Denis and colleagues have demonstrated that such skeletal descriptions are a very efficient way to describe a route (Denis, 1997; Denis & Briffault, 1997; Denis, Pazzaglia, Cornoldi, & Bertolo, 1999).

Large individual differences in the usage of verbal direction or maps might be another interpretation of the results (cf. Denis et al., 1999; Pazzaglia & De Beni, 2001). Some people are good with maps while others prefer verbal directions. While there are no doubts that individual preferences exist we do not think these differences are able to explain equal performance levels in this study. We controlled for sense of direction (Hegarty, Richardson, Montello, Lovelace & Subbiah, 2002), verbal and visuo-spatial ability as well as verbal and visuo-spatial memory with scales from standard tests like the German version of the Wechsler

Adult Intelligence Scale (Tewes, 1991). The scores could not account for the inter-individual variability in performance. Additionally, individual preferences for maps or directions could also not explain the better performance in giving directions compared to drawing maps. An alternative explanation for the null-difference between maps and directions is that map learners might have translated the maps into verbal directions. During the learning phase they generated a string of verbal expressions, e.g. "2nd right, 2nd right, left, 2nd right, left, left" for the short route. In this way they basically had the same mental representation as the direction-learners: a description. When both groups rely on this descriptive representation for wayfinding, this explains why no difference between map and directions could be found. Initial support for this account comes from the questionnaires in which all of our participants reported having translated the map into directions during memorising the map. However, there is also evidence for this account in our performance measures and in other experimental studies. First, in our study the participants made fewer errors in giving directions than in drawing the routes. This speaks for a language-based recoding of the maps. Second, participants performed better on the short route. We ensured that both routes were comparable in number of turns, intersections and alternatives (cf. Best, 1970; O'Neil, 1991). Participants on the long route performed worse within the mean time needed for navigating the short route. This excludes the time for maintaining instructions in memory as an explanation. The long route, however, contained mainly oblique intersections. Oblique intersections are more difficult to express verbally than the orthogonal intersections of the short route (cf. Klippel, 2003). Therefore, our verbal description of the long route consisted of 75 words the description for the short route of 35. Memorising more words from these directions or memorising more words from verbal re-coding of the maps, should be more error prone and, therefore, lead to worse wayfinding performance on the long route – this was exactly what we observed.

Support for the idea of language-based recoding of the maps also comes from other experimental investigations which found no differences between maps and directions (Schlender et al., 2000; Pazzaglia & De Beni, 2001) and from dual-task experiments. Garden, Cornoldi and Logie (2002) showed that a verbal shadowing task interferes with walking an unknown route and finding it immediately afterwards. Moreover, in this study the participants also reported to have relied heavily on verbal cues generated whilst learning the route. The second dual task experiment on wayfinding that supports our verbal re-coding theory comes from our own group. In Meilinger, Knauff, and Bülthoff (2006, submitted) we examined the working memory systems involved in human wayfinding. In a learning phase the participants learned the same routes as in the present study, now not in "real Tübingen" but in a photorealistic virtual environment simulation of Tübingen displayed on a 220° panoramic screen. While they learned the two routes they were occupied with a visual, a spatial, or a verbal secondary task. In the following wayfinding phase the participants had to find and to "virtually walk" the two routes again. In this study we showed that encoding wayfinding knowledge most strongly interfered with the verbal and the spatial secondary task, but only moderately with the visual secondary task. These results also speak against an alternative explanation in which the no-difference is due to the fact that the verbal directions are translated into a pictorial representation and so both directions and map users would rely on a pictorial representation. Obviously, this would not explain the pattern of interference in Meilinger et al. (2006, submitted) and it also does not explain the better performance in giving directions compared to drawing a map in the present experiment. It does not explain the introspective importance of verbal strategies in our present studies and in other related experiments (Garden et al., 2002; Meilinger et al., 2006, submitted) and it also does not explain why our participants acquired almost the same route and survey knowledge under the two learning conditions. A theory of verbal re-coding can explain these findings and might provide a good starting point for additional studies on the role of language and space in human wayfinding.

Maps and verbal directions enable us to find locations never visited before – a capacity only rarely encountered in the animal kingdom. Although language probably evolved as a solution for other problems than wayfinding, this could very well be one of language's manifold applications, enabling our astonishing performances not only in finding our way through the world.

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Appendix

Two examples of verbal directions used to construct the directions of the main experiment (translated from German).

Participant L.K.

Long route. Go straight on until you reach the next crossroad. Turn this road to the right. Straight on until there is another road on the left. Ignore this one and walk straight on until the next crossroad. There turn left until the next crossroad. There turn right in a sharp angle. Again, straight on quite a while until there is a road on the right. Ignore this one. Turn right at the next possibility. Turn left the next but one. Then straight on ignoring two roads on the right. Then turn left the next possibility. There is your goal.

Short route. Straight on. Turn right the 2nd possibility. Again turn right the 2nd possibility. Then turn left the 1st possibility. Then again turn right the 2nd possibility. Then turn left the first possibility and again turn left the 1st one.

Participant W.B.

Long route. Straight on, then turn right. 2nd intersection where you can't go any further. Then turn left. Then turn right. Again turn right the 2nd street. Turn left at the 2nd fork. Then turn left at the 1st street on the left.

Short route. Straight on to the 2nd intersection. Then turn right. Again to the 2nd intersection. Then turn right until you can't go on any further. Turn left until you can't go any further. Turn right. Again turn left until you can't go any further. Turn left.

From isovists via mental representations to behaviour: First steps toward closing the causal chain

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Abstract: This study addresses the interrelations between human wayfinding performance, the mental representation of routes, and the geometrical layout of path intersections. The virtual reality based empirical experiment consisted of a route learning and reproduction task and two choice reaction tasks measuring the acquired knowledge of route decision points. In order to relate the recorded behavioural data to the geometry of the environment, a specific adaptation of isovist-based spatial analysis was developed that accounts for directional bias in human spatial perception and representation. Taken together, the applied analyses provided conclusive evidence for correspondences between geometrical properties of environments as captured by isovists and their mental representation.

Keywords: isovist – geometry – wayfinding – spatial cognition – landmark knowledge – route knowledge – virtual reality

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1 Introduction

Although original space syntax measures mainly addressed relations between spatial structures and society, recently several researchers have applied these descriptions to quantify relations between environmental structures and individual behavioural responses (e.g., Conroy-Dalton, 2003; Haq & Zimring, 2003; Wiener & Franz, 2005). While the obvious success of these studies has backed this extension of the original scope of the analyses, conclusive explanations or insights into the mechanisms underlying these statistically observable patterns have not yet been provided. Unlike mindless agents, human beings normally do not solely respond to a given spatial stimulus, their navigation behaviour rather results from mental planning processes and the monitoring of goals, processes which are continuously updated according to the current perceptual context. Therefore, in order to proceed from the mere description of correlations between environmental structures and averaged spatial behaviour to qualified predictions and explanatory models, in other words to identify the causal processes which start from environmental structures and lead to behaviour, it seems necessary to determine the perceptual and mental processes underlying these behavioural patterns. As an initial step toward this long-term goal, this paper addresses the relevance of the geometrical information captured by isovists for mental representations.

In the following subsection, relevant literature regarding isovists and mental representations related to wayfinding is reviewed. In Section 2, we describe the experiment where participants learned and retraced two routes through a photorealistic virtual environment. Here also the methodology regarding isovists and mental representations is introduced. In Section 3 the results are presented. We discuss them in Section 4 with respect to literature both from the domain of spatial analysis and from the area of spatial cognition.

1.2 Space syntax, isovists, and visibility graphs

Space syntax is a set of technologies for the analysis of spatial configurations using simple graphs solely consisting of paths and nodes (Hillier, 1996, 1998; Hillier & Hanson, 1984). The techniques were developed in the late 1970 in order to analyze interrelations between spatial and social structures. This analytical reduction of space to mere topological mathematical information facilitates the calculation of characteristic values and the quantitative comparison of environments. Originally, space syntax was developed to analyze topological properties of large-scale spatial configurations from the room layout of building complexes to whole cities. Hence, these techniques deliberately abstracted from geometrical detail.

For analyzing geometry-related spatial characteristics of environments, Benedikt (1979) proposed *isovists* as objectively determinable basic elements. Isovists capture local spatial properties by collapsing the space visible from a single observation point to its two-dimensional abstraction. From these viewshed polygons, several quantitative geometrical descriptors can be derived such as area, perimeter length, or number of vertices. In a second step, these values can be mathematically combined to get further characteristic values. In order to better describe the geometry and also configurational characteristics of an environment as a whole, Turner, Doxa, O'Sullivan, & Penn (2001) have developed the technique of *visibility graph analysis* that combines aspects of global space syntax graphs with local intervisibility information as captured by isovists. Furthermore, this technique lends itself well for computer implementations. Although isovists describe abstract geometrical properties, recent research has shown that isovists are correlated with spatial behaviour and affective responses to indoor spaces (e.g., Franz, von der Heyde, & Bülthoff, 2005; Turner & Penn, 1999; Wiener & Franz, 2005).

Isovists basically describe local geometrical properties of spaces with respect to individual observation points and weight all possible view directions equally. Especially for the analysis of individual motion trajectories, sometimes also view-specific *partial isovists* have been applied (e.g., Conroy, 2001). Partial isovists consider only a restricted part of the theoretically available visual field (e.g., 90° instead of 360°). They correspond better to the restrictions of the human visual apparatus. Analogously, several studies have shown that humans encode spatial information from the point of view they encounter it (e.g., Christou & Bülthoff, 1999; Diwadkar & McNamara, 1997; Garsoffky, Schwan & Hesse, 2002; Mallot & Gillner, 2000).

Isovists are means to describe aspects of the outside world. As our goal is to reveal a connection between the geometric properties of the outside world and the inside world, we will now look what we store in our heads when walking around.

1.3 Knowledge in wayfinding

In the wayfinding literature the distinction between *landmark*, *route,* and *survey* knowledge has received a lot of attention (e.g., Golledge, 1999; Herrmann, Schweizer, Janzen & Katz, 1998; Kitchin and Freundschuh, 2000; Montello, Waller, Hegarty & Richardson, 2004; Piaget & Inhelder, 1967; Siegel & White, 1975). Landmarks are salient locations in the human environment such as a church or a square. *Landmark knowledge* refers to the recognition of these locations, e.g., "I know this esplanade, so I've been here before". Landmark knowledge alone is not sufficient to reach a goal. By recognizing a landmark, we know that we are on the right track, this however does not tell us, where to go next. The correct movement decision at an identified location requires route knowledge. *Route knowledge* describes the path that one must walk to reach the goal by telling the individual what to do at the decision points on the route, e.g., turn right at the church, then the second street to the left. It is one-dimensional or "string-like" and does not necessarily involve the knowledge of the exact location of the goal. *Survey knowledge*, in contrast, provides the direction and distance a location is to be found independent from knowing a path which leads there, e.g., the train station is about 300 Meters east from here. It is two-dimensional or "map-like". As survey knowledge is not route specific it will not be regarded further in this paper.

1.4 Predictions

Landmark and route knowledge together with wayfinding performance will be the dependant measures of our study. The different geometries of intersections expressed by isovist measures will be the independent measures of our study. Our prediction is that there is a connection not only between the geometry of intersections and wayfinding performance, but also between the geometry and mental representations, namely landmark and route knowledge.

Figure 1: The setup for learning and navigating the routes in Virtual Tübingen.

2 Methods

For the experiment we used a virtual environment displayed on a 220° semi-cylindrical screen. The participants learned two different routes through "Virtual Tübingen" a photorealistic model of the medieval city centre of Tübingen (see Figure 1, van Veen, Distler, Braun & Bülthoff, 1998). Directly after learning a route, participants had to find and to "virtually walk" this route with a joystick. After that we measured the acquired landmark and route knowledge with two choice reaction tasks. In order to represent expected directional biases, the isovist analysis made use of partial isovists capturing the perspectives seen when approaching the intersections. We validated this approach in the landmark knowledge task by comparing different perspectives of the intersections. Eleven isovist statistics were used to classify the intersections in two geometrically dissimilar groups. Then we compared the wayfinding performance and knowledge in these two groups of intersections. A second study was based on an analysis of the wayfinding data (Meilinger, Knauff & Bülthoff, 2006, submitted). This analysis was completely independent from the analysis done in the present study.

2.1 Knowledge and wayfinding performance

Participants. Twelve female and twelve male participants, mainly students between 19 and 32 (*M* = 24; *SD* = 4), participated in the experiment. None of them had visited Tübingen before. All selected participants were German native speakers and were paid for their participation. Two of original 26 participants did not complete the experiment due to simulator sickness and were therefore excluded from all subsequent analysis.

Learning the routes and wayfinding performance. The participants sat on a chair positioned at the focal point 3.5 meters away from a circular 220° screen (width: 13m, height: 3m), which covered the whole horizontal visual field (see Figure 1). A pc-cluster rendered the projection for an eye position 1.20 meter above the ground referring to an average eye-height in a seated position. The scene was rendered at a frame rate of 60Hz using 2 x hardware anti-aliasing and hardware correction to display the images geometrically correct on the curved screen. Three projectors with a resolution of 1024 x 768 each projected the pictures.

For learning the routes the participants were passively carried through the environment. The transportation speed was two meters per second corresponding to a fast walking speed. The long route spanned 480 meters and consisted of ten mainly oblique intersections with 23 possible choices (see Figure 2). Having a length of 320 meters, the short route contained nine mainly orthogonal intersections offering altogether 21 possible direction choices (for a further description of these routes see Meilinger & Knauff, submitted). The order of presentation of the routes was controlled. During route learning participants were confronted with either a verbal, a visual, a spatial, or no secondary task. This aspect of the experiment is described in more detail in Meilinger, Knauff and Bülthoff (2006, submitted).

No secondary task was applied when the participants actively navigated the routes immediately afterwards. Therefore, all participants had the chance to acquire knowledge without being distracted by a secondary task. During navigation, participants could control their heading and forward translation speed using a customary joystick device. The maximal translation speed was two meters

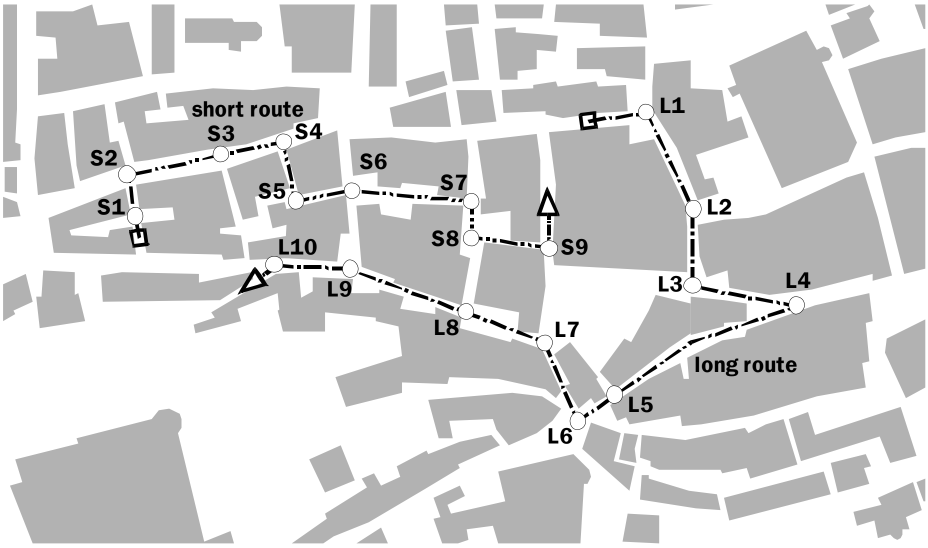

Figure 2: The two routes through Virtual Tübingen used in the experiment.

per second. In order to reduce simulator sickness, rotation speed was restricted to 30° per second.

The dependent variable *wayfinding performance* was measured by the proportion of correct route choices at specific intersections. When participants chose an incorrect route continuation, they were stopped after about 5 meters by the simulation. In this case they had to turn around in order to continue their navigation.

Before the experiment, participants were familiarized with the virtual reality setup and the joystick-based interaction in an area of Virtual Tübingen not encountered during the rest of the experiment.

Test of landmark knowledge. We measured landmark knowledge for intersections in a choice reaction task. Pictures of all intersections sized 1024 x 786 pixel were presented on a screen. In the pictures, the facades of houses situated in front of the intersection were visible (see Figure 3, left side). Participants had to press a button on a response box as fast as possible to indicate whether they had seen the intersection before. The same procedure was also used to test the perspective bias in recognizing intersections (see Section 2.2). The pictures presented were taken from every street approaching an intersection. So for a four arm intersection, four pictures had to be judged. 61 pictures of intersections and 8 distracters were presented this way. The distracters were pictures taken from intersections in virtual Tübingen not previously seen by the participants. All pictures were presented in random order. The positions of the hit and reject buttons on the response box were selected randomly for each participant. Accuracy and reaction times were recorded. Extreme values deviating more than three standard deviations from the mean were replaced by the most extreme value observed within three standard deviations.

Test of route knowledge. A choice reaction task was used to measure route knowledge. Pictures of intersections were presented, participants had to indicate the correct route continuation by deflecting a joystick in the correct direction as fast as possible (see Figure 3, right side). In case they were not able to recognize the intersection, they were instructed to deflect the joystick in a backward direction. The pictures used in the route knowledge test phase were identical to the pictures in the landmark knowledge task, but exclusively perspectives along the direction of travel were used. 19 pictures of intersections and 4 distracters were presented this way. Other distracters than in the landmark knowledge task were used that were also pictures from intersections not previously seen by the participants. Pictures and distracters were presented in random order separated by routes. Each picture and distracter was presented twice. Accuracy and reaction times were recorded. The correction of extreme values was identical like in landmark knowledge.

Figure 3: To measure their landmark and route knowledge, participants saw pictures like the one on the left side. For route knowledge the participants indicated the further route with a joystick as seen on the right side.

2.2 Test of perspective-dependent and geometry-dependent recognition biases

We wanted to test whether the directed route presentation and exploration in the initial learning phase of the experiment led to a stronger memorization of this particular perspective. Therefore, we analyzed the data obtained from the landmark recognition task (see landmark knowledge) on direction-specific differences. For this purpose, the performance in discriminating a picture of an intersection from a distracter d' was computed for each perspective of an intersection (Green & Swets, 1966). The statistic d' expresses the difference between the normal distribution of stimuli and the normal distribution of distracters in standard deviations. A d' of 1.0 means that the two distributions are one standard deviation apart. If a participant recognized all distracters or targets, d' could not be computed. In this case a recognition rate of 100% was replaced by a 99% score. The perspective seen when approaching the intersection was expected to be recognized more easily compared to perspectives in a 90° or 180° angle to this perspective. Reaction times and d' in these groups of pictures were compared within-subject using an ANOVA with post-hoc t-tests.

2.3 The direction-specific isovist analysis

Isovists. The differential analysis between intersections described above required a quantitative description of the individual intersections. In order to test whether expected differences could be attributed to some visuo-spatial properties, a quantitative description of the intersections' geometrical layout and shape based on isovists was calculated. Isovists, as originally conceived by Benedikt (1979), equally describe all possible view directions from a given single observation point, a perspective which is directly perceptible only in an unnatural bird's eye view of a spatial environment. In reality, however, observers experience the environment mainly from a directed inside perspective along their main line of travel, suggesting a different weighting of view directions depending on their relative angle to this main direction. In order to account for this in the isovist-based spatial analysis, two specific adaptations were introduced: First, instead of basing the analysis on ordinary 360° isovists, directed partial isovists spanning a horizontal angle of 90° were applied (cf. Conroy, 2001). Second, in order to include also information on branchings beyond this restricted angle, the reference points of the isovists were shifted from the center of the intersection in the direction the intersection was approached from. Thus the isovists corresponded to the visual field as available immediately before entering the junctions. (cf. Figure 3 left side and Figure 4).

The eleven isovist-based geometrical descriptors of the junctions were calculated using the free ajanachara tool (Franz, 2003) which offers both isovist and visibility graph-based statistics. The visibility graph analysis was done at a spatial resolution of 1.5 meters, i.e., squares with 1.5 meters length represented either walls or open space. Table 1 gives a short overview of the individual variables which comprised typical local geometrical measures from the isovist literature. For more detailed information, please refer to Franz and Wiener (2005).

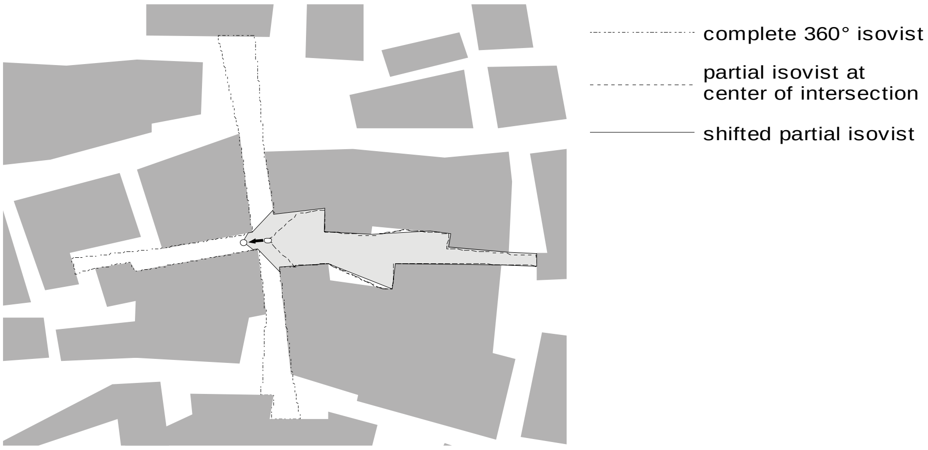

Figure 4: Exemplary illustration of the applied partial isovist analysis (intersection S6). The analysis accounted for the directed perspective participants experienced the environments. In order to do so the reference points of the partial isovists was shifted into the direction of approach, which is to the left in this example.

Isovist Statistic	*Short Description*
Area	Number of 1.5 m x 1.5 m squares lying with at least 50% inside the isovist
Perimeter length	Overall length of the isovist boundary
Vertices	Number of vertices of the isovist polygon
Vertices per perimeter	Number of vertices divided by perimeter
Vertices per area	Number of vertices divided by area
Roundness	Isovist area divided by squared perimeter length
Jaggedness	Squared Perimeter length divided by area
Bounding proportion	Length of the principal axis of a minimal bounding rectangle divided by its secondary axis
Convexity	Roundness divided by bounding properties. A measure for the deviation of the isovist from a rectangle
Openness	Length of open edges dived by length of closed edges. Closed edges are visible walls, open edges result from occlusions
Clustering	Percentage of pairs of squares in the isovist which can see each other

Table 1: Description of the eleven isovist statistics used in the analysis comparing the geometrical characteristics of the junctions

Isovist-based categorization of intersections. Based on the eleven isovist statistics obtained by the analysis described in the previous section, a measure of geometrical similarity of the intersections was calculated. Since isovist statistics typically correlate highly with each other, first, a factor analysis was applied to identify independent dimensions underlying these parameters (e.g., Backhaus, Erichson, Plinke, & Weiber, 1990; Kim & Mueller, 1978). A principal component analysis extracted factors with an eigenvalue > 1.0 out of the correlation matrix. In order to do so, the isovist statistics were correlated with each other over the intersections. A multiple linear regressing estimated the communalities. The resulting factor matrix was rotated using the VARIMAX method. Each intersection could be described now by their factor values on three independent factors. A hierarchical cluster analysis grouped the intersections on basis of these factor values using Euclidean distances and the Ward method to compute distances between groups of intersections e.g., Backhaus et al., 1990; Everitt, 1993). The last two groups of intersections to be clustered together were taken as geometrically distinctive groups of intersections. To see if participants reacted differently to these geometric layouts, navigation performance, landmark knowledge, and route knowledge on these two groups of intersections were compared with each other in t-tests.

3 Results

3.1 Perspective-bias in recognition

To tell whether the perspective seen when approaching an intersection was the most relevant, different perspectives of intersections were compared in the landmark knowledge task. We computed the performance in discriminating the different perspectives of intersections from the distracters. The performances differed due to the angle between the perspective the picture was taken and the direction of traveling (see Figure 4; d': $F(2, 46) = 29.8$, $p < .001$, $\eta^2 = .56$; reaction time: $F(2, 46) = 12.8$, $p < .001$, $\eta^2 = .36$). Pictures taken along the direction of traveling (0°) were recognized better compared to pictures taken from 90° to that (d': $t(23) = 10.2$, $p < .001$, effect size = 2.08; reaction time: $t(23) = 4.12$, $p < .001$, effect size = 0.84) or taken from 180° (d': $t(23) = 3.84$, $p < .001$, effect size = 0.78; reaction time: $t(23) = 4.42$, $p < .001$, effect size = 0.90). Pictures taken from 90° were recognized worse than pictures taken from 180° (d': $t(23) = 3.05$, $p = .006$, effect size = 0.62; reaction time: $t(23) = 1.15$, $p = .262$, effect size = 0.23).

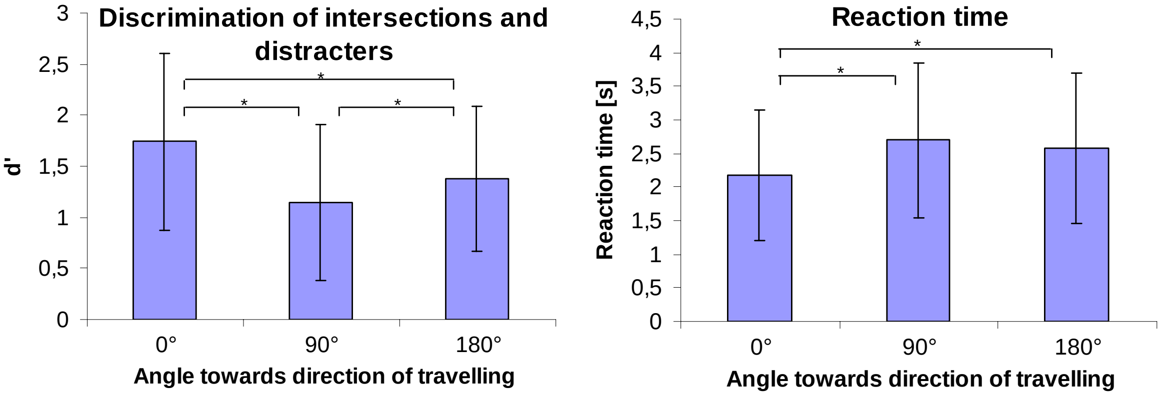

Figure 4: d' values expressing the performance of differentiation between distracters and pictures of intersections (left) and reaction times (right). The pictures of the intersections were taken from the direction the intersections were approached originally (0°) or from an angle of 90° or 180° to that direction. Means and standard deviations are displayed. Asterisks mark significant differences at $p < .05$.

3.2 Isovist analysis

We used an isovist analysis to identify two groups of geometrically different intersections and relate them to navigation performance and knowledge measures. The space visible when approaching an intersection was expressed in eleven isovist statistics. A principal component analysis identified three independent factors with an eigenvalue > 1 underlying the eleven highly correlated isovist measures (see Table 2). Geometrically similar intersections show similar isovist statistics and therefore also similar values on the underlying factors.

	Factor 1	*Factor 2*	*Factor 3*
Vertices	0,89	-0,11	-0,13
Bounding properties	0,88	-0,24	-0,03
Convexity	-0,76	0,35	0,46
Area	0,67	-0,57	0,18
Perimeter	0,69	-0,62	-0,21
Roundness	-0,65	0,54	0,50
Vertices per perimeter	-0,28	0,92	0,16
Vertices per area	-0,26	0,93	0,01
Clustering	-0,12	0,37	0,84
Openness	-0,01	0,33	-0,82
Jaggedness	0,51	-0,45	-0,64

Table 2: The rotated component matrix with the loadings of the isovist statistics on the three independent factors. Grey shading indicate higher loadings. This means that the factor expresses much of the variance of this isovist statistic

A hierarchical cluster analysis grouped the intersections successively based on their geometrical similarity expressed in similar values in theses three independent factors. First, very similar single intersections were grouped together.

Then, similar groups were merged together until in the end only two groups remained before being merged together (see Figure 5). These last two groups consisted of T-intersections that are the intersections S5, S7, S9, L1, L3 and L4 in contrast to the non-T-intersections. These two groups of intersection differ in the geometry seen when approaching the intersection: At a T-intersection, one sees a wall in front and two route alternatives to the right and to the left. The same intersection would be classified differently when approached from a different direction, as here a street would branch of from a straight main street.

The performance on theses two groups of geometrically different intersections was compared. At non-T-intersections the participants clearly performed better than at T-intersections (see Table 3). The participants recognized non-T-intersections faster than T-intersections ($t(22) = 2.51$, $p = .020$; accuracy $t(23) = 1.21$, $p = .238$). At

	T-intersections	*Non-T-intersections*	*Effect size*
Landmark knowledge			
Accuracy	0.55 (0.20)	0.62 (0.22)	0.25
Reaction time* [s]	2.62 (1.43)	2.22 (1.03)	0.52
Route knowledge			
Accuracy*	0.42 (0.21)	0.61 (0.16)	0.96
Reaction time [s]	2.51 (1.01)	2.41 (0.97)	0.16
Wayfinding performance per intersection			
Getting lost*	0.19 (0.18)	0.12 (0.13)	0.52

Table 3: Mean performance (with standard deviations) at T and non-T-intersections and effect sizes for the differences. Asterisks mark significant differences at $p < .05$

non-T-intersections the accuracy in indicating the further route was higher compared to T-intersections ($t(23) = 4.71$, $p < .001$; reaction time $t(22) = 0.76$, $p = .457$). At T-intersections the participants got lost more often than at non-T-intersections ($t(23) = 2.56$, $p = .017$). The geometry of intersections was associated not only with different wayfinding performance but also with different landmark and route knowledge.

4 Discussion

The present study examined the connection between geometrical properties of our environment and mental representations of this environment. The main finding is that geometrical properties are not only connected with directly observable wayfinding behaviour (e.g., Conroy-Dalton, 2003; Haq & Zimring, 2003; Wiener & Franz, 2005), but that they are also connected with mental representations of this environment. T-intersections and non-T-intersections were the geometrically most dissimilar subgroups of intersections as revealed by isovist statistics. At T-intersections participants performed worse in the active navigation task as well as in the landmark and route knowledge tasks.

What could be reasons for this difference between T and non-T-intersections? Generally, T-intersections might be geometrically more similar with each other than non-T-intersections which could be branch-offs, cross-intersections or even more complex intersections. A higher similarity might lead to more confusions and therefore to a lower performance in wayfinding as well as landmark and route knowledge (cf. Figure 6).

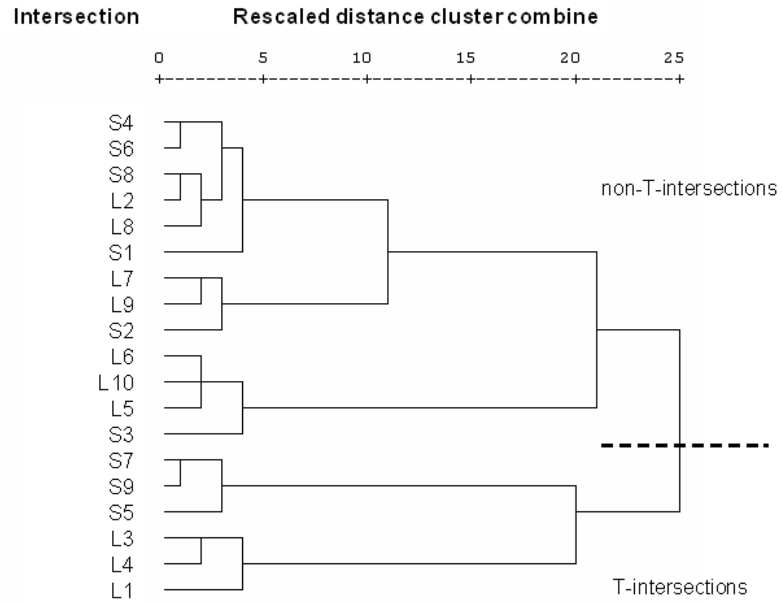

Figure 5: Dentrogram of the hierarchical cluster analysis. Vertically all 19 intersections of the two routes are displayed. To the right is the Euclidian distance between intersections or groups of intersections in the three-dimensional space created by the three independent factors. Intersections or groups of intersections are grouped together at a certain Euclidian distance. Geometrically similar intersections are grouped at short distances, dissimilar ones at large distances.

Figure 6: Two T-intersections on the short route. At the left intersection (S7) a participant had to turn to the right or to indicate so in the route knowledge task. At the right intersection (S9) a participant had to turn to the left.

For both route knowledge and navigation performance, the observed better performance at non-T-intersections must be a very robust effect. In both measures, participants had to choose between alternatives. With more alternatives the task gets more difficult to solve by guessing (O'Neill, 1991a; 1991b). At non-T-intersections, the participants had to choose between 2.4 alternative routes in average whereas at T-intersections the participants only had to choose between 2 alternatives. Despite this higher chance level at non-T-intersections, participants performed better, indicating a strong effect even overriding this bias.

A second important point of this study is the inclusion of perspectivity in the isovist analysis. First, we did not apply isovist statistics with a 360° field of view as is most commonly done, but limited the field of view by applying partial isovists (cf. Conroy-Dalton, 2003). Second, the isovists' reference points were shifted towards the approach direction. This approach is in accordance with anatomical constraints of the human visual apparatus and directly corresponds to the directional route presentation. It is in accordance with studies showing that humans encode spatial information from the point of view they encounter them, at least for environments not too familiar (e.g., Christou & Bülthoff, 1999; Diwadkar & McNamara, 1997; Garsoffky, Schwan & Hesse, 2002; Mallot & Gillner, 2000). In addition, we validated this approach by comparing the recognition performance of intersections. Analogous to the directional bias in the analysis, participants recognised intersections best when shown a picture taken along the direction of traveling. If perspectivity did not matter participants should have recognized the intersections equally well from all perspectives. Although the optimal angular size of partial isovists is object to future studies, one important conclusion can be drawn: As captured by the applied method, a T-intersection is psychologically different from a topologically equivalent branch off. This holds true also if the geometry of both intersections is identical.

In order to close the gap between isovist statistics and wayfinding behaviour by accounting for perception and mental representations, the correct consideration of perspectivity seems crucial. The acquisition of mental representations, however, is only one part of what happens in the brain during wayfinding. In order to make use of this information, the brain has to process these representations. Several strategies and heuristics how to process these representations have been proposed, e.g., the least-angle strategy (e.g., Hochmair & Frank, 2002). Other strategies like hierarchical fine-to-coarse planning (Wiener, Schnee & Mallot, 2004) or sticking to well-known areas as much as possible have been proposed (Hölscher, Meilinger, Vrachliotis, Brösamle & Knauff, 2005). Based on the outcomes of this study, this multitude of strategies can be complemented by another heuristic which could be informally termed 'when-in-doubt-follow-your-nose'. We compared the performance at intersections where participants had to walk straight on with those intersections which required a turning. Participants recalled these two groups of intersections equally well (see Table 4 landmark knowledge; accuracy: $t(23) = 0.65$, $p = .520$; reaction time: $t(22) = 1.10$, $p = .282$). When asked to draw the routes including *all* intersections, they made less errors at drawing intersections which required a turn than at drawing intersections where the route went straight on ($t(23) = 3.52$, $p = .002$). Despite the equal to better memory for intersections requiring a turn, participants performed better at "straight-on" intersections when they had to decide for the further route. Participants correctly indicated to walk straight on more often than they indicated a correct turn (see Table 4 route knowledge; accuracy: $t(23) = 3.44$, $p = .002$; reaction time: $t(23) = 1.51$, $p = .145$). They also got lost less often at intersections where no turn was required ($t(23) = 3.58$, $p = .002$). We think that participants decided to walk straight on when they did not remember the further route. This 'when-in-doubt-follow-your-nose' strategy can reduce memory demands. Thus, participants only had to store and recall changes in the direction of travel. It was not necessary to recall where to go at straight-on intersections, because here the default strategy of walking straight on applies. In principle, one alternative explanation would be that participants had to walk straight on most of the times and that these results are therefore specific for these routes. This explanation could not hold true as participants had to walk straight on less often (7 times) than they were required to turn (12 times).

	Route goes straight on	*Turn required*	*Effect size*
*Errors at drawing intersections**			
	4.4 (2.0)	2.5 (2.4)	0.72
Landmark knowledge			
Accuracy	0.58 (0.26)	0.61 (0.17)	0.13
Reaction time [s]	2.22 (1.11)	2.39 (1.17)	0.23
Route knowledge			
Accuracy*	0.65 (0.18)	0.49 (0.18)	0.70
Reaction time [s]	2.29 (1.06)	2.52 (0.95)	0.31
Wayfinding performance per intersection			
Getting lost*	0.06 (0.09)	0.19 (0.18)	0.73

Table 4: Mean performance (with standard deviations) at intersections where to walk straight on or with a turn required. Asterisks mark significant differences at $p < .05$

We described the 'when-in-doubt-follow-your-nose' strategy for retracing a route and for the memory of a route. The tendency of walking straight on has already been described for exploring an unknown virtual environment (Conroy, 2001). Here participants rather walk straight on than turn at an intersection.

We presented various results in this paper. When interpreting and generalizing these results, one has to take especially two aspects into account. First, the results may not be interpreted causally. Not only geometry, but also any other environmental property correlated with geometry could be a relevant cause for the observed differences. Second, the experiment took place in a typical European city centre with lots of different intersections. The results might be limited to such geometrically rich environments. In a typical American rectangular grid like city layout with geometrical very similar intersections, geometry might play a less important role for wayfinding.

5 Conclusions

Confirming the outcomes of many other studies, this paper has shown that isovist analysis is a powerful tool for quantitatively capturing behaviourally relevant geometric properties of environments. Beyond this, the presented study demonstrated for the first time correspondences between mental representations and geometric properties captured by isovists. Furthermore, this paper pointed towards the importance of perspectivity when predicting human behaviour. Although a street branching-off and a T-intersection might be identical in their abstract geometric and topological layout, they are different psychologically: the very same intersection could be a T-intersection and a street branching off, depending from where it is approached. Considering perspectivity, as in the conducted analysis, is one important point when closing the gap between an isovist analysis on one hand and predicted behaviour on the other hand. We are convinced that this gap can only be closed when taking mental representations and processes into account. The authors hope that this approach is a step not only towards closing the gap between space syntax analysis and behaviour but also towards narrowing the gap between architecture and spatial cognition.

Acknowledgements

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3.4 Up the down staircase

Up the down staircase: Wayfinding strategies in multi-level buildings

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Abstract: The intention of this article is to create a link between human spatial cognition research and architectural design. We conducted an empirical study with human subjects in a complex multi-level building and compare thinking aloud protocols and performance measures of experienced and inexperienced participants in different wayfinding tasks. Three specific strategies for navigation in multi-level buildings were compared. The central point strategy relies on well-known parts of the building; the direction strategy relies on routes that first head towards the horizontal position of the goal, while the floor strategy relies on routes that first head towards the vertical position of the goal. We show that the floor strategy was preferred by experienced participants over the other strategies and was overall tied to better wayfinding performance. Route knowledge showed a greater impact on wayfinding performance compared to survey knowledge. A cognitive-architectural analysis of the building revealed seven possible causes for navigation problems. Especially the staircase design was identified as a major wayfinding obstacle. Finally we address the benefits of cognitive approaches for the architectural design process and describe some open issues for further research.

Keywords: cognition - architecture - wayfinding strategies - survey knowledge - usability

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"To experience architectural space truthfully it is
necessary to perambulate and stride the building."
Le Corbusier (1962, p. 30)

1 Introduction

Many people have problems finding their way around public buildings such as airports, hospitals, offices or university buildings. The problem may partially lie in their spatio-cognitive abilities, but also in an architecture that only rudimentarily accounts for human spatial cognition. We aim to make progress towards linking architectural design and human spatial cognition research. The paper begins with an overview of relevant previous work on wayfinding cognition. In the main part of the paper we report on an empirical investigation in which twelve participants solved wayfinding problems in a complex multi-level building. Half of the participants were very familiar with the building; the other half were visiting the site the first time. The results reveal distinct differences in the navigation strategies of familiar and unfamiliar participants in their strategy choice. We discuss how these strategy and performance differences may relate to route- and survey-based knowledge and to reference frames. We provide a detailed architectural analysis of the building and discuss the generalizability of our findings for architectural design, human spatial cognition research, and indoor-wayfinding.

1.1 Environmental features and wayfinding difficulties

What are the environmental features that can lead to navigation breakdowns? A pioneering study on indoor navigation was conducted by Best (1970), who first identified fundamental aspects of a building's route network, like choice points, directional changes and distances as relevant predictors of wayfinding difficulties in complex buildings. Numerous studies, especially in the environmental psychology community, have since investigated the reasons for wayfinding difficulties. For instance, Weisman's (1981) identifies four general classes of environmental variables that shape wayfinding situations: visual access, the degree of architectural differentiation, the use of signs and room numbers, and floorplan configuration. Further studies pointed to the impact of layout complexity on both wayfinding performance and cognitive mapping (Gärling et al., 1986; O'Neill 1991a/b). Recent studies have been conducted in airports (e.g., Raubal, 2002), shopping malls (Dogu & Erkip, 2000) and universities (Abu-Obeid, 1998; Butler, Acquino, Hissong & Scott, 1993).

Another essential point seems to be the familiarity with the building. Gärling et al. (1983) point out that familiarity with a building has substantial impact on wayfinding performance. So does visual access within the building: If large parts of the building are immediately visible and mutual intervisibility (vistas) connects the parts of the building, people have to rely less on stored spatial knowledge and can rely on information directly available in their field of vision, a notion inspired by Gibson (1979). A disadvantage of these lines of research is that floorplan complexity and configuration as well as visual access have been defined rather informally in the literature discussed above (e.g., by subjective ratings). The concept of *isovists* (Benedikt, 1979) provides a much more precise mathematical framework for capturing local properties of visible spaces as viewshed polygons, which correspond with psychological measurements of environmental perception (Stamps, 2002). The Space Syntax movement (Hillier & Hanson, 1984) has introduced formalized, graph-based accounts of layout configurations into architectural analysis. Calculations based on these representations express the connective structure of rooms and circulation areas in a building and are strongly associated with route choices of hospital visitors both in unguided exploration and in directed search tasks wayfinding behavior (Peponis et al., 1990; Haq & Zimring, 2003). Yet research along this methodology is generally based on correlations of building layout and aggregate movement patterns, thus providing no immediate understanding of individual cognitive processes (Penn, 2003).

1.2 Wayfinding in three-dimensional structures

One drawback of almost all controlled studies into wayfinding performance and building complexity is that they have limited themselves to investigating movement and orientation in the horizontal plane of isolated floor levels (with notable exceptions like Hunt, 1984; Moeser, 1988). Soeda, Kushiyama and Ohno (1997) observed wayfinding performance in tasks involving vertical level changes. They found people losing their orientation due to vertical travel, supporting more informal results of Passini (1992). Soeda et al. (1997) identified another challenge of multi-level buildings: Wayfinders assume that the topology of the floorplans of different levels is identical, an assumption that can lead to severe wayfinding difficulties.

In Section 2.2 of the paper we provide a building analysis revealing that our setting could be similarly prone to challenges based on multi-level properties. Therefore, our investigations into both the navigation performance of test participants as well as their mental processes explicitly focus on the above-mentioned aspects. Montello and Pick (1993), although not investigating wayfinding behavior directly, present evidence that humans have trouble correctly aligning vertical spaces in pointing tasks. We also expect wayfinders to have trouble integrating survey knowledge of different floors. Properly connecting mental floorplans at transition points like staircases or elevators may also be further impaired by difficulties of maintaining one's heading due to the rapid direction changes involved in stair climbing.

1.3 Wayfinding strategies for complex buildings

Authors like Weisman (1981) or Lawton (1996) have analyzed wayfinding strategies as to what degree they rely on different types of knowledge. Spatial knowledge is commonly distinguished into three levels (Siegel & White, 1975). In the context of this study it can be assumed that finding destinations inside the building requires all three types of spatial knowledge: landmarks identify one's own position and relevant navigational choice points, route knowledge connects distinguishable landmarks, while survey knowledge integrates routes and guides high-level decisions for route selection and general direction. Pazzaglia and De Beni (2001) found evidence that people differ in their general preference for relying on different types of spatial knowledge, especially landmarks vs. survey knowledge. Lawton (1996) implies that people's wayfinding strategies gradually progress from route-based orientation to survey-based strategies, yet could not clearly tie this evolution to a performance improvement. Yet it has become clear in recent years (Montello, 1998; Montello, Waller, Hegarty & Richardson, 2004) that strict developmental stages from landmark, to route and then survey knowledge are not realistic and that the representations rather develop in parallel, so that navigators can build up initial survey representations early on.

In a building with a complex network like in our study, the general notion of survey knowledge – in the sense of correct positional information about the metric spatial position of destinations – representing the most advanced and valuable information one may not hold. In fact, knowing the routes through the maze of levels and vertical and horizontal corridors can be even more important, especially since seemingly direct routes may be blocked by dead-ends in the building, an aspect not taken into account by direction-based navigation planning.

A number of different wayfinding strategies have been described for two-dimensional (outdoor) settings. Both Hochmair and Frank (2002) and Conroy Dalton (2003; Conroy, 2001) have described *least-angle strategies*: People try to minimize their global deviation from the direction of the goal position, and at the same time avoid local direction deviations at junctions, thus maintaining a straight heading wherever possible. Wiener, Schnee and Mallot (2004) were able to show that navigators in a virtual outdoor environment rely on *region-based strategie*s of *fine-to-coarse* planning with a hierarchical planning approach: The environment is cognitively segmented into regions which guide navigation decisions.

But how do people incorporate their available knowledge in wayfinding strategies in the three-dimensional case of multi-level buildings? We propose a distinction of three strategies for finding one's way, even in cases when the way-finder does not have fully developed knowledge about the spatial setting:

1. The *central point strategy* of finding one's way by sticking as much as possible to well-known parts of the building, like the main entry hall and main connecting corridors, even if this requires considerable detours.

2. The *direction strategy* of choosing routes that head towards and lead to the *horizontal* position of the goal as directly as possible, irrespective of level-changes.
3. The *floor strategy* of first finding one's way to the floor of the destination, irrespective of the horizontal position of the goal.

Mapping these strategies to other accounts, the least-angle strategies can be directly related to the direction strategy in our classification. In a more abstract sense, the region-based „fine-to-coarse" strategy of – ceteris paribus – preferring paths that quickly bring one into the region of a destination, is compatible with the floor strategy, if you assume floor levels as organizing principles in the mental representation of multi-level buildings (cf. Montello & Pick, 1993). The idea of a route *skeleton* proposed by Kuipers et al. (2003) corresponds to the central-point strategy. Kuipers et al. showed that over time, human as well as artificial navigators learn a set of central paths ('the skeleton') in an environment. This centrality can be predicted based on the number of boundary relations involved in its segments, but we can also assume that architects mark certain paths as central by architectural features like entries or ornamentation. Also, the notion of a frame of reference which relates to the main orientation of an environment unless sticking to the orientation the environment was initially experienced (e.g., McNamara & Valiquette, 2004) might be interpreted in the sense of a central point strategy. The main corridors correspond to main orientation of the building and they are the first parts of the building to be experienced. If the whole building is encoded with respect to this reference frame as proposed by McNamara, using theses corridors like in the central point strategy should be easier for participants. Yet it is not a priori clear whether or not a reliance on central points and paths will have more positive or negative impact on navigation performance, especially in our setting.

1.4 Knowledge about the environment

The application of the strategies defined above clearly requires access to information about the building. Allen (1999, p. 51) provides a taxonomy of wayfinding means and tasks relative to available knowledge about the environment. With an environment as complex as the building in our setting, the relevant types of knowledge can become quite intertwined. To address this, we look into the knowledge requirements from three perspectives:

First, the overall familiarity of the wayfinders with the building is controlled for by comparing a group of visitors unfamiliar with the building to a group of repeat visitors. Second, survey knowledge about the building is identified for each participant in a pointing task. And third, in a self report measure of environmental ability the competence to build up environmental knowledge is assessed.

This design, combined with verbal reports and task performance measures, will allow us to address the following research questions as well as methodological concerns:

1. Which *strategies* do wayfinders employ for navigating in the third dimension?
2. How does *familiarity* with the building affect performance and the choice of navigation strategies?
3. What is the role of *survey knowledge* for multi-level wayfinding performance?
4. Which cognitive processes can be identified in *verbal reports* of wayfinding tasks and how do they relate to performance?

2 Methods

The majority of experimental studies on human wayfinding behavior and related cognitive competencies are based on direct observation of navigator behavior. We agree with Passini (1992) that the collection of wayfinding behavior data can successfully be complemented with verbal reports of task-concurrent thoughts to get a comprehensive picture, especially in exploratory studies. Hence, we introduce verbal reports of wayfinders as an additional data source. The *thinking aloud method* of collecting verbalisations concurrent with task performance is an established method for tapping into those cognitive processes that can be verbally accessed (Ericsson & Simon, 1993). Passini (1992) based his seminal qualitative investigations into wayfinding processes on the extensive analysis of individual wayfinding episodes and the verbal comments of his test participants. Our study aims at a somewhat more formalized approach to qualitative verbal data by quantifying occurrences of verbal reports and comparing these with behavioral measures like time, distance, pointing accuracy and objective route choice since verbal reports of, for example, strategic decisions alone may not be sufficiently reliable. In multi-level buildings with complex floorplans involving inconsistencies and dead-end routes, planning processes and adequate route choice strategies should be very important for wayfinding success. Therefore, our thinking aloud analysis of cognitive processes focuses on the degree of planning, the type of environmental information perused (signs, visual access, etc.) and strategic reasoning.

2.1 Participants

Participants were attendees of an annual summer school for human and machine intelligence which takes place at the Heinrich-Lübke Haus, a conference centre in Günne, near Düsseldorf, Germany. Seven women and five men were asked if they would volunteer in a wayfinding experiment. Six of them were familiar with the

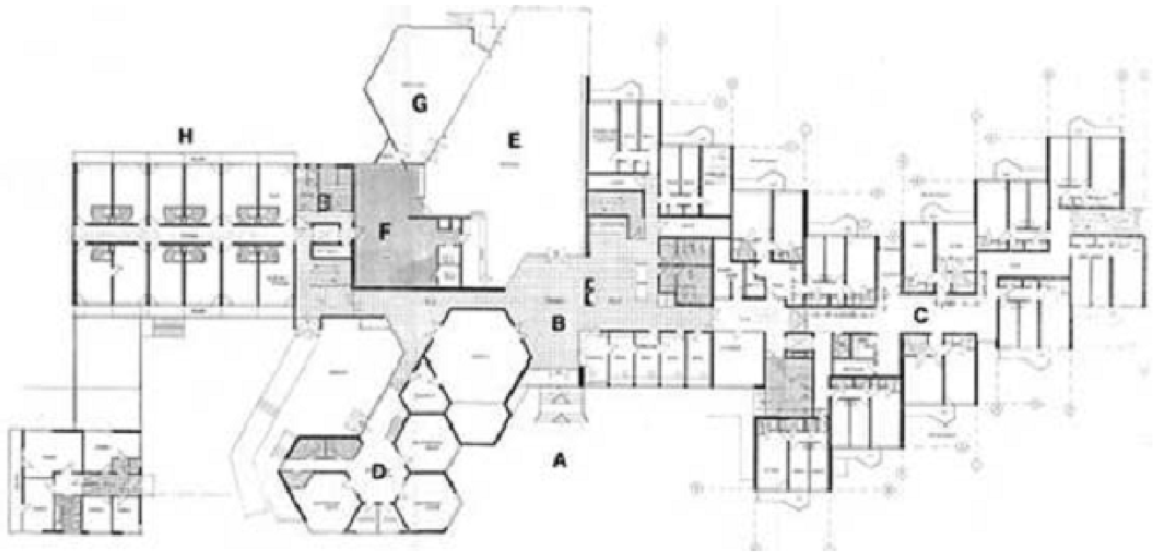

Figure 1: Ground plan: (A) Public entrance (B) Entrance hall (C) Living quarters (D) Commons - communication and leisure area (E) Dining-room (F) Kitchen (G) Coffee bar (H) Lecture rooms.

building.[1] They had previously visited the one-week conference at least two times and therefore knew the building well. The six participants unfamiliar with the building (three of them were women) visited this years' conference for the first time. Their sessions took place within the first three days after their arrival. All participants were in their mid-twenties to mid-thirties and were all native German speakers.

2.2 Building analysis

The conference centre was built in 1970. We explore the ground floor (level 0) of the multi-functional building to exemplify the general characteristics and spatial organization of the layout (see Figure 1). The common layout consists of various simple geometrical elements that are arranged in a complex and multi-faceted architectural setting. In the theory of architectural design, building structures can be formally understood from diverse points of view, as a group of voids or solids (Mitchell, 1990). Consequently, this building is subdivided into a well-designed group of solids with void space between them. Additionally, each group of solids implies various functions, e.g., the living quarters (C) have a quadratic design style and the communication area (D) a hexagonal design style. With this in mind the building can be architecturally categorized as an "indoor city" (Uzzell, 1995) as it is composed of a small ensemble of units and a large public circulation area. The main path of walking through the building is an axial one rather than a cyclical one, which means one has to pass the central point (B) frequently when traveling between areas.

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[1] Due to technical reasons, performance on task1 (anchor) was only analyzed for five of the six familiar participants.

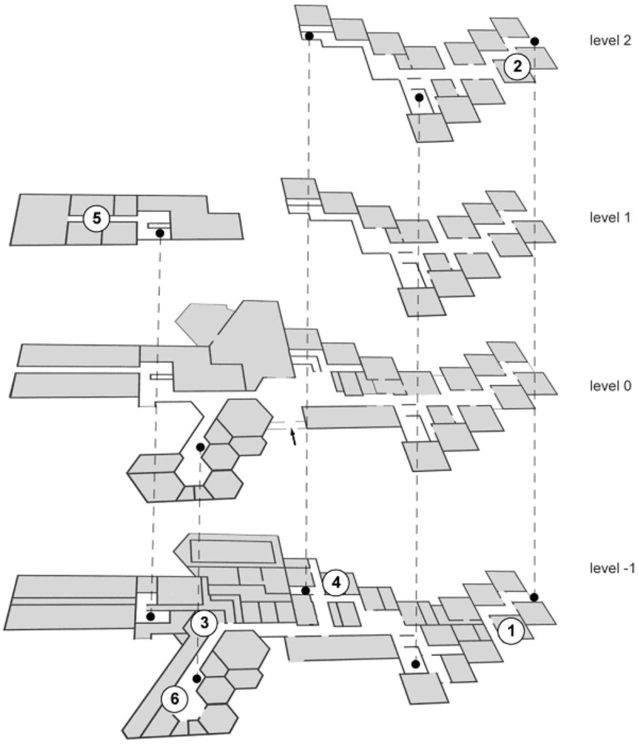

Figure 2: The floors of the building with circulation areas. Stairways are illustrated as vertical connections. Starting points and goals of the navigation tasks are marked by numbers. First, participants had to reach point 1 (anchor), from there point 2 (room 308) and so on.

Changing floors in the building exemplifies its spatial complexity and vertical impenetrability. As one can see in Figure 2 the layout of the hallways on every floor seems to be one and the same, but is actually different for each floor. For example, the configuration of the ground floor (level 0) and the basement (level -1) differs significantly. As a result of this counter-intuitive layout, the user has to repeatedly look for a new and unknown route on every level.

2.3 Procedure

In this building, the participants' task was to find six locations. The participants were filmed with a camera and had to verbalise their thoughts. Between wayfinding tasks they had to point to four locations they had previously visited in order to assess their survey knowledge. The whole experiment lasted about 45 minutes including the instruction, as well as an interview and debriefing after the experiment.

First, the participants were instructed to think aloud while performing the wayfinding tasks and not to pay attention to the camera. During the whole experiment they were not allowed to use floor maps or ask other people for advice, but they were allowed to use signs or to look out of the window for orientation as long as they stayed inside. For most task instructions the experimenter just mentioned the goal such as "Find room number 308".

All participants received the tasks in the same order, as each destination point is the start location for the following task, making randomization unfeasible. Throughout this paper, navigation tasks are identified by numbers, pointing tasks by capital letters:

1 From outside the building, the participants were shown a wooden *anchor* sculpture inside the living quarters. They had to find it from the main entrance without leaving the building again.

2 The goal was to find *room 308.*

3 Participants had to navigate to the *bowling alley*. It was located in the cellar of the building, where the locations for all leisure activities were to be found.

4 The *swimming pool* could also be found there.

A From the swimming pool the participants had to point to the *anchor*, the destination of the first task.

B After moving a few meters away from the swimming pool the participants were asked to point to the *forecourt* in front of the main entrance.

5 The participants had to navigate their way to the *lecture room number four.*

C From a point close to (or near) the lecture rooms, the participants had to point to the *bowling alley.*

6 The final navigation task's destination was the *billiard table.*

D From the billiard table they had to point back to the *lecture rooms.*

2.4 Dependent measures

Objective measures - performance. For each task, the shortest route as well as a list of reasonable route alternatives was determined beforehand. Reasonable routes are defined as neither containing cycles nor dead ends or obvious detours. Each observed route alternative was categorized for its compatibility with the three wayfinding strategies (central point, direction and floor strategy; see section 1.4) and employed as the behavioural measure of strategy use. This categorisation was based on the navigation decisions at each choice point, which could be compatible, neutral or incompatible with each of the three strategies. Two raters had to come to an agreement regarding the categorisation.

Navigation performance was measured with six variables: (1) time to complete the task, taken from the video; (2) stops; (3) getting lost, i.e., number of times participants left a *reasonable route alternative* and showed detour behavior; (4)

distance covered; (5) distance covered divided by length of the shortest possible route. (This parameter expresses the proportion of superfluous way independent of task length. E.g., a value of 1.35 can be interpreted as walking 35% farther than necessary); (6) speed (distance covered divided by the time to reach the goal).

Subjective measures - verbal protocols. The second group of measures classified the participants' verbal comments. To "quantify" the qualitative data the analyses were completed in three steps. First, prior to the analyses, a coding schema for classifying the verbal comments was developed according to Krippendorff (1980). The initial coding scheme was developed based on a pilot session to determine what types of verbalisations can be related to categories of theoretical interest. Second, the walked route for each participant and each task was drawn into the plans of the building. This was used to determine distances of routes and superfluous way after getting lost (see above). Third, the verbal codes and stops were written beside this drawn route at the location they were mentioned. This was done by two independent raters in a step-by-step fashion. The coding scheme was incrementally refined so that categories could be reliably recognized by the two raters, based on the video sequences of four participants. This process was repeated until a sufficient inter-rater reliability with a kappa value of .7 ("substantial" reliability according to Landis & Koch, 1977) was reached. To reduce coding error, every participant was coded twice and in case of disagreement one consensual rating was achieved. In addition to the verbalization categories, the participants' remarks about their strategies were collected for every task.

Out of the mentioned strategies for each task, the preferred one was identified by the raters where possible. Four subjectively preferred strategies could be identified: The already described direction, floor and central point strategy (see section 1.4) and, in addition to that, the "route is well-known" strategy when participants mentioned walking a route completely familiar to them (see also, Hochmair & Raubal, 2002).

Survey knowledge. From their current position the participant had to point his/her arm in the direction of a location previously visited during this experiment. The pointing arm was filmed from several perspectives, so that the pointing direction could be clearly identified afterwards. The position of the participant and the pointing direction were transferred from the video to a map. On this basis, the angular deviation from the correct direction was determined. Taking into account that the pointing error is to the right (negative angle) or to the left (positive angle), the mean is a measure of the systematic error, specific to each pointing task. The unsystematic error can be measured by the standard deviation (cf. Wang & Spelke, 2000).

Sense of direction. The subjective sense of directions was measured by the Freiburg version of the Santa Barbara Sense of Direction Scale – FSBSOD (Hegarty et al., 2002; Meilinger & Knauff, submitted; FSBSOD, 2004). It consists of 15 questions concerning spatial ability e.g. "I am very good at giving directions". After leaving the conference the participants were asked via e-mail to fill out an online questionnaire. This procedure inhibited direct influences from the task performed in the experimental session on the self-ratings (cf. Hegarty et al., 2002).

3 Results

First, general aspects of the process of navigation as expressed in the verbalisation and their interrelations to performance are presented and the tasks are compared according to these measures. Second, for the central part of the analysis we look at the impact of wayfinding strategies. Finally, the influence of familiarity and survey knowledge on verbalized cognitive processes, navigation strategies and task performance is presented.

In the two rightmost columns of Table 1 the average performance and standard deviation per task are shown[1]. The participants needed almost two minutes to cover the average 100 meter distance which is 36% more than the shortest possible way. They stopped about once per task and lost their way 0.3 times.

The verbalisations mentioned during these tasks are shown in Table 2. 40% of all verbalisations were reflections mainly about the building. 22% refer to partial planning, 12% to landmark checks during plan execution (like "here is the fire place") and 9% to usage of signs. Remaining categories each make up for 5% or less of the utterances.

	Anchor	*Room 308*	*Bowling alley*	*Swimm-ing pool*	*Lecture room 4*	*Billiard table*	*M*	*SD*
Time [s]	226	78	159	34	103	81	112	78
Stops [n]	2.8	0.4	1.7	0.3	0.5	0.9	1.1	1.80
Getting lost [n]	0.7	0.1	0.5	0.0	0.3	0.2	0.3	0.57
Distance [m]	168	84	127	40	113	87	102	58
Way/shortest way	1.68	1.24	1.71	1.00	1.08	1.50	1.36	0.59
Speed [m/s]	0.74	1.08	0.81	1.28	1.12	1.10	1.03	0.29

Table 1: Average performance in each task and the average performance and standard deviation across all tasks

3.1 Tasks

Do the wayfinding tasks cover a broad range of difficulty? To answer this question, performance was compared between tasks in an ANOVA for each dependent measure. The tasks differed in all performance measures (see Table 1, all six $F(5, 65) > 3.0$, $p < .016$, $\eta 2 > .19$). The most difficult task was finding an

Verbalisation category	*Description*	*Fre-quency [n]*	*Pro-potion [%]*
Complete plan□	A complete plan covers a path from the current location to the destination of the current task	13	3
Partial plan*	A non-complete plan contains uncertainty and/or covers only parts of a complete path	87	22
Search	Systematic number-based search, e.g., to find a room	17	4
Correct reflection	Reflections about the building that are correct.	18	5
False reflection	Reflections about the building that are incorrect.	7	2
Reflection*	General reflections and assumptions, not only about the building	130	33
Alternatives*	Consideration of more than one possible route to the goal	16	4
Failed plan□	Failure of a pursued plan	11	3
Identify landmark	Recognition of a known landmark in sight	48	12
Outside orientation	Use of the outside space for orientation	14	4
Sign	Participants mention a sign in sight	34	9
Sum		395	100

Table 2: The verbalisation categories & their frequency and proportion across all tasks. An asterisk* marks a significant difference in average frequency between tasks ($p < .05$), a cross□ marks a statistical trend ($p < .10$).

anchor shown from outside of the building. The participants stopped and got lost most often and they covered the longest distance at the lowest average speed.[2] Both in the anchor task and in the bowling alley task – the second most difficult task – the covered distance was 70% longer than in the shortest possible route. In the bowling alley task (task 3, Figure 2) many alternative routes were available. Here stopping and getting lost happened second most often, and speed was the second lowest. By the same variables, the billiard task (task 6) can be considered third in its degree of difficulty. The easiest task was the pool task (task 4). No one got lost, there was no superfluous distance covered, stops were least frequent and therefore the speed was highest. So there was a clear variation in task difficulty as intended.

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[2] Stops and getting lost can be considered dependent of length of the task, but normalising them on navigation time or the shortest possible way did not produce a different pattern of results and so the average per task, which is easier to interpret, was taken. From a theoretical point of view, this parameter is also favourable, as the number of intersections, number of turns, etc., are more important for difficulty than mere length of the route.

3.2 Strategies

Most of the participants voiced remarks concerning the strategy they used to find their goal. Sometimes they switched their strategy during a task, but in 61 cases a preferred strategy could be identified by the raters.

Different strategies were chosen in different tasks (not shown here, χ^2 (15, N = 61) = 56.9, p < .001, w = 0.97). In the easiest task, the swimming pool task, all identified strategies relied on the well-known route. In the two most difficult tasks (anchor and bowling alley), many participants chose a direction strategy. For these tasks, the precise goal location was largely unknown for the participants. Contrarily, in the also often unknown task 2 (Room 308), the floor strategy was chosen most frequently. Assuming that the floor strategy is efficient, its application might explain the good results in this task.

To test this, performance according to the preferred strategy has to be considered. As strategy choice was dependant on the tasks and the tasks differ in difficulty, the influence of the tasks had to be partialed out, i.e., controlled statistically as a covariate in an ANOVA. So the benefit of the strategies could be compared independently of the tasks. As shown in Table 3 best performance was achieved when walking a well-known route (except stops all five $F(3, 56) > 3.1$, $p < .035$, $\eta^2 > .14$). Not surprisingly, here the absolute and relative distance as well as time was shortest, speed highest and getting lost occurred least often. When using the direction strategy or the central point strategy, the absolute and relative distance as well as time measures indicated the worst performance. With a central point strategy participants to some extent walked known (sub-) routes and therefore could walk quite fast without getting lost. But as the routes were longer than in other strategies, it took longer to reach the goal. With the direction strategy participants got lost more often and reorientation takes time, so that average speed dropped. The same amount of time was needed to reach the goal as in the central point strategy, even though the distance was shorter. The floor strategy resulted in better performance with respect to *both* distance and time, thus avoiding the relative deficits of the central point and direction strategy.

Partialed out means	*Central point strategy*	*Direction strategy*	*Floor strategy*	*Route is well-known*
Time [s] *	140	145	113	67
Stops [n]	1.05	1.50	1.62	0.18
Getting lost [n] *	0.23	0.69	0.35	0.03
Distance [m] *	142	119	97	68
Way/shortest way*	1.86	1.38	1.33	1.06
Speed [m/s] *	1.04	0.86	0.96	1.29

Table 3: Average performance per task solved with the preferred strategy. The influence of task difficulty is partialed out.

The differences between the strategies can also be identified in the navigation process itself, manifested in the verbalisations (see Figure 3, all described differences F(3,56) > 2.9, $p < .044$, $\eta^2 > .13$). Again, walking a known route was quite different from the other strategies: participants most often planned their route completely, while overall fewer verbalisations of other processes were uttered when this strategy was used. Presumably these participants just relied on their readily stored (route) knowledge and did not need further reasoning. Participants using a central point strategy most often searched systematically, used signs most often and tended to identify landmarks most often (F(3,56) = 2.58, p = .062, $\eta^2 = .12$) as well as planned their route only partially (F(3,56) = 2.56, p = .059, $\eta^2 = .12$). Participants using a direction strategy mentioned the highest number of correct reflections and general reflections.

Strategy choice can be determined by objective route choice and subjective mentioned strategies. How closely are they related? Very similar results according to both performance measures and verbalisations were found when the selected route alternative was considered instead of the subjective mentioning of a strategy. In addition, the subjective and objective strategy indicators are directly connected. Even if a well-known route can not be assigned to a specific route, subjective direction, floor and central point strategy are highly correlated with the objective choice of route: Route choices according to a certain strategy goes along with mentioning this strategy significantly more often (N = 59; direction strategy: $\chi^2(1) = 11.8$, p = .001, w = 0.45; floor strategy: $\chi^2(1) = 8.11$, p = .004, w = 0.37; central point strategy: $\chi^2(1) = 21.1$, p < .001, w = 0.60).

3.3 The Role of familiarity

Because of their greater knowledge about the building, familiar participants are assumed to show better performance – is this true? Indeed, familiar participants performed better (see Table 4). They got lost less often, covered a shorter distance

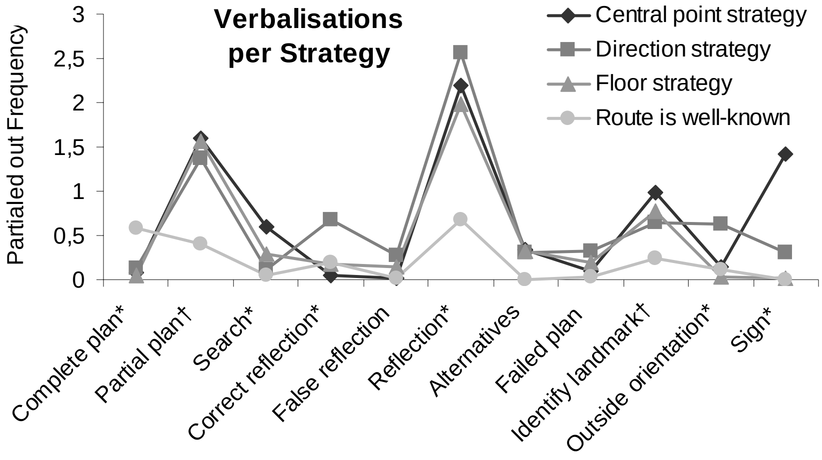

Figure 3: Average verbalisations per task solved with the preferred strategy. The influence of task difficulty is partialed out.

	Unfamiliar		*Familiar*	
Performance	*M*	*SD*	*M*	*SD*
Time [s] *	128	22	95	21
Stops [n]	1.36	0.69	0.78	0.80
Getting lost [n] *	0.42	0.17	0.17	0.21
Distance [m] *	115	16	89	17
Way/shortest way*	1.55	0.22	1.17	0.16
Speed [m/s] *	0.96	0.06	1.10	0.09

Table 4: Means and standard deviations of the performance with different degree of familiarity

(absolute & relative), with greater speed, and therefore reached the goal more quickly (all six t(10) > 2.23, p < .05, ES > 0.77).

Familiar participants performed better in reaching a goal. But can this difference be traced back to different processes during navigation? As shown in Figure 4 they more often completely planned their route (unless stated otherwise, all t(10) > 2.26, p < .048, ES > 1.30), whereas unfamiliar participants tended towards more partial planning (t(10) = 1.91, p = .085, ES = 1.10). There was a trend for unfamiliar participants to utter more reflections (t(10) = 1.92, p = .084, ES = 1.09) and to identify more landmarks (t(10) = 2.13, p = .059, ES = 1.21). Unfamiliar participants also needed to search more as well as to orient themselves more towards signs and the outside of the building.

Familiar participants were able to rely on their (route-related) knowledge for execution whereas unfamiliar participants needed to process more local information from the building and from outside. Can this difference also be found in the choice of strategies? Indeed, familiar and unfamiliar participants differed in their preferred strategies (see Figure 5, $\chi^2(3, N = 61) = 19.0$, $p < .001$, w = 0.56). Participants unfamiliar with the building most often chose the central point strategy and almost never walked a well-known route, whereas participants who

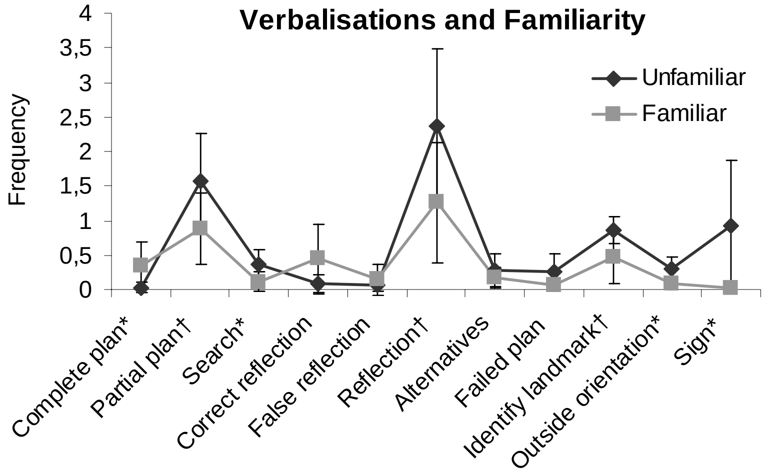

Figure 4: Means and standard deviations of verbalisations as a function of familiarity.

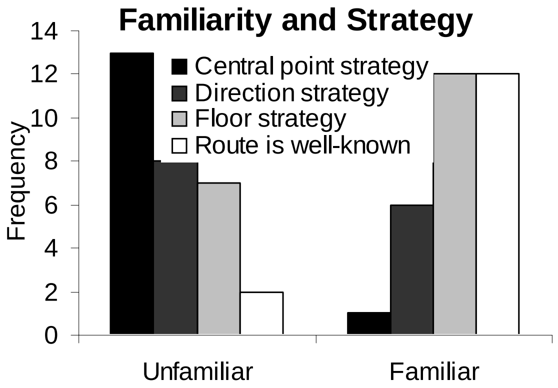

Figure 5: Frequencies of strategy selection as a function of familiarity.

knew the building almost never chose a central point strategy and most often either walked a well-known route or used a floor strategy. The direction strategy was equally used by both groups.

3.4 Survey knowledge

If survey knowledge is the crucial factor for the good navigation performance, pointing performance should differ due to familiarity. But in the four pointing tasks no difference could be found in the systematic error expressed in the mean pointing error (although these tests are not orthogonal, see Figure 6, all four $t(10) > 1.21$, $p > .252$, median ES = 0.32). For the unsystematic error expressed in the standard deviation, there was a trend in pointing task A for a smaller pointing error in unfamiliar participants ($F(5,5) = 3.90$, $p < .10$) and there was a smaller pointing error in familiar participants D ($F(5,5) = 388$, $p < .001$). So, except for task D, no indication of better survey knowledge due to familiarity was found.[3]

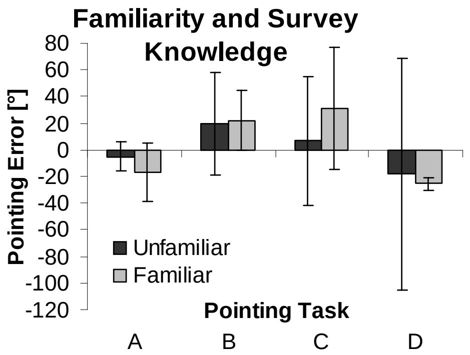

Figure 6: Pointing errors in the four pointing tasks in familiar and unfamiliar participants. Pointing to the left of the correct direction resulted in a positive error, pointing to the right in a negative one. The systematic pointing error is displayed in the mean deviation from the right pointing direction, the unsystematic error in the standard deviation.

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[3] An additional analysis of absolute pointing error as a combined measure of systematic and unsystematic error revealed the same pattern of results.

To obtain a more direct and sensitive test for the influence of survey knowledge on navigation, the sample was bisected into good vs. bad pointers according to their average absolute pointing error across the four tasks. However, in this analysis also no differences could be revealed for navigation performance measures (all six t(10) > 1.30, p > .221, median ES = 0.11). Even among the eleven verbalisation categories only a single difference was found: good pointers uttered more correct reflections (t(10) = 2.60, p = .026, ES = 0.90). Survey knowledge did not explain differences in performance and verbalisation.

3.5 Sense of direction

Nine out of twelve participants completed the online questionnaire. While for the behavioural measures reported above we did not find any gender differences, women did considered themselves to have a poorer sense of direction than men did (t(6.84) = 2.703, p = .031, ES = 1.65) in the self-rating questionnaire. Good pointers achieved higher questionnaire scores (t(7) = 3.423, p = .011, ES = 2.20). No differences in sense of direction due to familiarity were found (t(7) = 0.939, p = .379, ES = 0.61). No significant correlations between average performance of a participant and her/his sense of direction could be found (n = 9, all six r < .50, p > .173). Participants with a good sense of direction rating uttered more correct reflections (n = 9, r = .76, p = .018) and tended to utter less references to landmarks (n = 9, r = .60, p = .089; all other verbalizations r < .53, p > .141). No correlation between sense of direction and the strategic preferences of a participant (as measured by the number of tasks he or she tackled with each of the available strategies) could be revealed (all three r < .25, p > .531). Overall, the SBSOD scores revealed as little relation to navigation performance in our setting as the survey knowledge measured with the pointing tasks (section 3.4).

4 Discussion of empirical results

The present study was conducted to explore wayfinding strategies in a complex indoor environment and their relations to the user's knowledge. The experiment provides quantitative behavioral and verbal data, as well as the opportunity to observe deficits of the building with respect to wayfinding usability. In the next sections we first discuss the main quantitative results. Then we link the experimental data collection to architectural design. We analyze seven "hotspots" of the building and explain why they make it so hard to find a way through the building.

Our study follows a strategy of methodological triangulation by combining verbal data and behavioural observation to collect a large data set from each participant to adequately reflect the complexity and variability of navigation behavior in a real life setting. Each participant had to complete a battery of six wayfinding tasks over a range of spatial sub-settings and covering a considerable span of difficulty (as demonstrated in section 3.1). This measure was taken to increase the ecological validity and generalizability of our findings. Due to this approach, the number of participants of our study may appear relatively limited. Yet the statistical results do show that our sample size was adequate for the setting. At the heart of the empirical part of our paper lies the analysis of strategies (section 3.2) and experience (3.3). The tests revealed the expected significant results and we report the corresponding effect sizes (Cohen, 1988) for all tests in addition to the significance values. Obtaining significance despite a small sample size is generally only possible with substantial underlying effect sizes. The effect sizes (w, η^2 and ES scores, see above) for all tests reported as significant correspond to at least "large effect sizes" according to Cohen (1988). Furthermore, the statistical analyses reported on parametric statistics were replicated with non-parametric tests as well, yielding the same pattern of results (Siegel & Castellan, 1988). We have reported the parametric measures prominently, since for part of the analysis we needed to statistically control for task difficulty, a feature not available with non-parametric testing.

The main finding of our study is that different indoor wayfinding strategies could be identified on a subjective and an objective level and that these strategies correspond to specific differences in cognitive processes and performance measures. The shortest and fastest way to reach a goal was to walk a well-known route. If that was not possible – e.g., because the goal or part of the way to it was unknown – the floor strategy was the best alternative in our scenario. Walking via a central point or going directly in the assumed direction of the goal led to clearly worse performance.

The second finding is that participants familiar with the building more often relied on their knowledge and they walked a well-known route that they had completely planned in advance. In doing so they navigated faster than unfamiliar participants taking the same route. If that was not possible, they chose another efficient strategy, the floor strategy, leading to shorter navigation distances and times. With their knowledge familiar participants did not have to collect as much information from their surroundings as unfamiliar participants, who had to search and look at signs as well as looking outside. This led to a clearly better performance.[4] In a task new even to participants familiar with the building, differences vanished.

Our third finding is related to the impact of survey knowledge. In this study survey knowledge did not correspond to wayfinding performance and a clear superiority of familiar participants with respect to survey knowledge could not be established. The errors in task D is surprising as this was the only pointing task which could be solved by path integration: the participants just had to remember the direction of the starting point of their last navigation task. As this was not

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[4] A similar comparison between women and men did not reveal any gender differences.

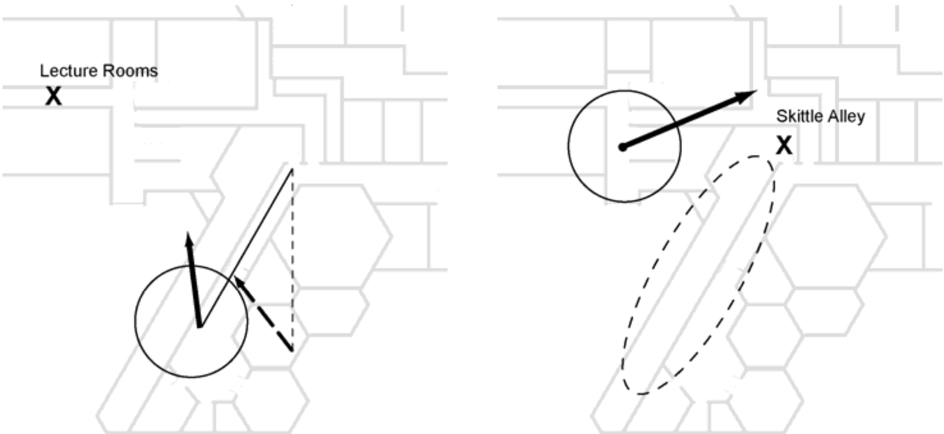

Figure 7: Starting (circle) and goal point (cross) in pointing task D (left). The mean pointing direction is marked with the arrow in the circle. If you assume that the participants remembered a right angle between the parts of the building and not the correct 60fl, pointing from the assumed place (dotted line and arrow) is quite accurate. Pointing performance for task C is shown on the right side.

possible in the other tasks one would expect the best results in task D, not the worst ones. But taking into account that this was the only task where the parts of the building the participants pointed from and to did not lie at a right angle to each other but at 60° (see Figure 7, left), the systematic error can be explained. A person remembering a 90° angle instead of the correct 60° one would locate him/herself standing on the start of the (dotted) arrow to the right and not at the start of the arrow to the left. From this position the mean pointing direction would be quite accurate. Similar results are found in pointing (e.g., Thorndyke & Hayes-Roth, 1982) and in map drawing (e.g., Gillner & Mallot, 1998).

We also found that complete planning is associated with good performance, while reflecting, partial planning and re-planning is tied to poor performance. Verbal reports alone must be interpreted with caution as they are restricted to consciously accessible aspects of cognitive processes (Ericsson & Simon, 1993). Thus it is important to note that in our study we have identified wayfinding strategies on a *subjective* and an *objective* level with converging results: The shortest and fastest way to reach a goal is by using one's knowledge to walk a well-known route, as most familiar participants do. If that is not possible, for example because the goal is unknown, the wayfinder has to rely one of three heuristic strategies (floor, direction or central point strategy) to find her goal. In such a situation familiar participants dominantly choose the floor strategy, that turns out to be the best alternative in our scenario. Walking via a central point - like most unfamiliar participants do - is clearly less efficient, and going directly in the assumed goal direction leads to higher levels of navigation errors. Consequently both the direction and the central point strategy proved less favourable in our scenario.

Survey knowledge – as measured by pointing performance – could not account for the wayfinding differences, as even with familiar participants systematic errors in survey knowledge prevail. Overall, unfamiliar participants verbalise more. Assuming that this requires more (cognitive) resources and therefore makes unfamiliar participants slower could explain their poor performance. But referring to the strategies, one reason for poor performance is unfamiliar participants taking long and winding routes like in the central point strategy or getting lost as in the direction strategy. Slowness alone can not account for that.

According to the classical view of Siegel & White (1975) one would expect the familiar participants' wayfinding advantage to be based on clearly more elaborate survey knowledge compared to unfamiliar participants. Although the classical view including developmental steps is not shared anymore (Montello, et al., 2004), e.g. we are able to build up survey knowledge from a map (e.g. Moeser, 1988) and photo slides rather quickly (Holding & Holding, 1989), familiarity *does* facilitate the acquisition of survey knowledge (Montello et al., 2004). Why could the familiarity difference not be explained by survey knowledge? Is it the small number of participants, since in this part of the analysis the pattern of effect sizes is less clear cut? For other variables of theoretical merit reliable effects could be found in our study, and for the pointing variables even the direction of the differences often is not in favour of familiar participants.

Maybe measuring pointing *after* the navigation task is the reason. Previously existing differences in survey knowledge could account for the better navigation performance in familiar participants. But by walking the routes unfamiliar participants were able to acquire this survey knowledge, reduce the difference and perform equally well in the pointing task afterwards. To test that, pointing performance would have to be measured before navigating a route. But also individual differences in sense of direction (FSBSOD) – known to be related with tasks requiring survey knowledge – did not correlate reliably with performance (Hegarty et al., 2002; Kozlowsky & Bryant, 1977). This might be due to the even smaller number of participants, but still sense of direction was interrelated with inter-individual pointing performance and higher scores for males, who are known to perform better in tasks requiring survey knowledge. Therefore it is also possible that survey knowledge is not as much of a key issue in reaching a goal as route knowledge is. Meilinger and Knauff (submitted) were able to show that in an outdoor setting available and memorized survey knowledge (in the form of maps) did not lead to better performance in finding a novel route compared to bare route knowledge (in the form of verbal descriptions). Relying on a direction strategy led to worse performance. Indoors, this may be even more pronounced, since dead-ends and limited connectedness of floors and paths make survey and direction-related knowledge even less useful here. Further support for our tentative view is provided by the fact that the strategy exclusively dependent on survey knowledge – the direction strategy – is accompanied with getting lost and relatively bad performance. Also, searching systematically is not associated with bad performance and the two tasks including systematic search are solved quite well. Overall the failure of survey knowledge to show any clear correspondence with wayfinding performance at least casts a shadow of doubt on its predominant relevance for indoor navigation.

Yet we must bear in mind that the building in this study may also have some characteristics limiting the generalizability of the results, especially with respect to survey knowledge. Gaining a survey representation of the individual floors is not overly complex, as there is always one core route per floor. But the pointing tasks in this building require the integration of survey knowledge across levels. Even with the study by Montello and Pick (1993), it is an open question, whether people actually possess an integrated 3D representation of a building, or if this needs to be computed on the fly in a potentially error-prone manner, because the survey representations of floors are stored independently. This integration of survey representations across floors may still be difficult even for the experienced visitors of the building. As pointed out in section 1.2, the current study is one of very few attempts to approach this 3D integration challenge. We believe that our analysis of strategies characteristic for 3D navigation provides some initial access to the issue of representing 3D space:

The advantage of the floor strategy can be interpreted as a result of a hierarchical planning process. Ants are known to store 3D movements in form of a horizontal projection (Wohlgemuth, Ronacher & Wehner, 2001). Human performance declines if they have to use pitch rotations to explore a VR labyrinth (Vidal, Amorim & Berthoz, 2004). Therefore we might store the different levels of a building separately in memory rather than construct a 3D mental model of the building. This makes navigational decisions more difficult that require an integration of vertical and horizontal aspects. The floor strategy avoids this integration bottleneck with a hierarchical route planning heuristic: First we change to the corresponding vertical level and once we have reached it, the fine planning is reduced to a two-dimensional problem space. In terms of Wiener et al.'s (2004) fine-to-coarse planning our *floor strategy* can thus be interpreted as a 3D variant of the cognitively efficient regionalisation strategy.

As a design consequence, the floor strategy, which is most efficient for unknown goals in multi-level buildings, should be supported by easy transitions between the floors. Also, the systematic search is to be taken into account with systematic room numbers or informative signs.

5 Cognitive-architectural analysis

Architecture deals with the design, construction and conceptualization of built space. It greatly influences the comprehension and knowledge of orientation and navigation systems. Akin (2002) clarifies that the architect aims to construct buildings as complex systems of numerous architectural dimensions. To develop an adequate and satisfactory compromise is an essentially spatial task. Architectural space is not generated on a blank sheet, but constantly in respect to the present environment and consequently in a high-dimensional decision space (Bertel, Freksa & Vrachliotis, 2004).

More than 40 years ago Le Corbusier emphasized the idea of movement as a central theme in the theory of architectural design—see the epigraph to this paper. We agree that the perception of a built environment must be described as a dynamic process of movement caused by the fact that we do not experience the spatial layout of a building as a static structure. We discover architectural shapes and layouts literally step by step. Thus, from a user's perspective several points of environmental ability, legibility (Lynch, 1960) and imageability (Passini, 1992) are essential to understand and interpret building layouts, e.g., landmarks, routes, paths and walkways, and to differentiate shapes and forms, configured space and building topology, and the close relation between inside and outside space. "The idea or image of a building is as important as the building itself" characterized David Stea (1974, p. 157) as the connection between architectural space and its mental image.

Understanding a building from its inside structure and spatial organization requires making one's way through the building. Thus, in theories of building design, the idea of architectural experience and the meanings of walkways have a very close relationship. From a Space Syntax's point of view walkways seems to be the most fundamental aspect of architectural space, not only for investigating pedestrian movement in designed environments but also for general exploring, discovering and learning about architectural settings. In order to provide useful spatial points of reference, the differentiation and discrimination of shapes is the most central property in planning an architectural setting. Although symmetry and similarity are very well-known features in the history of architecture, they contrast with the indispensable need of distinguishing multi-faceted environments. Symmetrical architectural settings are principally one of the foremost difficulties in spatial problem solving processes (Remolina & Kuipers, 2004). Yet, they can be helpful in interpreting vertical information of space, e.g., for spatial reasoning within multi-level buildings (Montello & Pick, 1993).

5.1 Analysis of Usability Hotspots in the Conference Facility

Overall, we believe the functional dilemma of the building for wayfinding is prominently caused by the problematic arrangement of complex decision points, their linking paths, the position and design of stairways, vertical incongruence of floors, incomprehensible signage, and too few possibilities for monitoring interior and exterior landmarks. Consequently, the building as a whole gives the impression of a three-dimensional maze. In the following, we focus on seven "hotspots" of the building and describe their disadvantages from a cognitive-architectural point of view.

Hotspot 1: Entrance hall. The entrance hall is indiscernible. For public buildings the entrance hall symbolizes the most important point in the layout. The public entrance (see Figure 1, A) as well as the large entrance hall (Figure 1, B), the two central points of the conference center, are comparatively indiscernible, although they are centrally positioned in the general configuration of the building. The essential function of the entrance hall is to be readable as such and to cognitively structure the route network, especially for unfamiliar visitors, who clearly rely on central-point-based strategies, as we have discussed earlier (cf. McNamara & Valiquette, 2004). However, this function is not properly met, which imposes a usability deficit on the building as a whole. For the user entering the entrance hall, there is an immense lack of survey as well as little visual access to areas relevant for the legibility of the spatial situation of the building (see Figure 8, providing the *isovist* from the center of the entrance hall). The entrance hall doesn't make the navigation choices visible to the user; especially the stairways are invisible from the entrance hall.

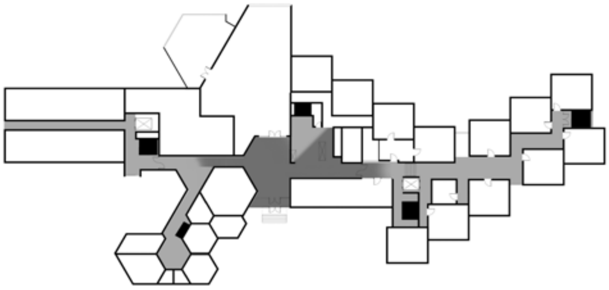

Figure 8: Location of stairways (black boxes) and isovist (area of visual access) from the main entrances hall (darker gray shaded area in center).

Hotspot 2: Survey places. The building lacks survey places. Especially within complex spatial settings architects and designers have to create places of survey and overview to allow users to build well-integrated spatial knowledge. Visibility is one of the most important qualities of architectural spaces and consequently fundamental to the general understanding of built environments. Even on the ground floor of this conference center there are not enough areas of open space to familiarize oneself with the environment, neither with the interior space (e.g., visual axis) nor with the exterior surroundings (e.g., inside-outside relationship). A striking example of this is the basement with its leisure facilities. It was compared to an area in the entrance hall paralleled in size and alternatives. Far from giving a good overview, the entrance hall is still better than the basement. And indeed comparing these two areas, there were significantly more stops in the basement (16 vs. 6: $t(10) = 3.079$, $p = .01$), yet no differences in the frequency of getting lost (these are more closely related to dead ends and stairways design, see below).

Hotspot 3: Floors. The layout of the floors is incongruent. In the planning of complex buildings architects have to pay attention to the uncomplicated and insightful organization of floors. The floors of the conference center give the impression of matching one another, but in fact the hallways are considerably different (see Figure 2). From wayfinding research and a building usability point of view, this a) prompts improper assumptions in the users about the route networks and b) hampers the mental alignment of levels. Pointing task C (bowling alley, see Figure 7, right) illustrates the problem: Although the bowling alley is directly ahead and extends to the right, participants systematically point left, presumably because they misalign their current position with respect to the floor below, due to inconsistent hallways (ground floor vs. basement) in this area.

Hotspot 4: Dead ends. Dead ends make wayfinding difficult. It is very important in architecture and particularly for public buildings such as universities, hospitals or conference centers to pay attention to always provide an alternative route to any navigational decision. Dead ends block the user's exploration activity and are extremely difficult to operate within the mental representation of the building in respect to the levels above and vertical information in general. But there are several locations that can be characterized as "dead space", "dead ends" or "blind alleys" (Figure 1 & 2). For example, the public area surrounded by the living quarters leads to a dark and uncomfortable corridor. Users will not expect the stairways at the end of the corridor (far right in Figure1 & 2) and thus miss relevant route choices and feel lost in dead ends. We observed a total of 17 episodes of getting lost in our experiment. Five of these episodes (29%) were directly caused by the fact that the participant was stuck in one of the two dead ends in the basement (the far right and far left parts of the basement level in Figure 2).

Hotspot 5: Interior building structure. The interior building structure is not distinguishable. To understand a building layout both the exterior and the interior structure of a public building has to be effortlessly understood. Looking at the floor plan (see Figure 1), the dissimilarity of geometrical shapes and architectural forms would appear to be helpful for the users to orientate themselves. But in fact, when actually navigating in the building, the different subsections are no longer readily recognizable for the wayfinder, leading to a lack of visual differentiation.

Hotspot 6: Public and private space. There is too little differentiation of public and private space. When planning multi-functional public buildings architects have to bear in mind to separate private or personal space from public space. This rule serves the purpose of integrating two disparate spatial systems within one building. There are a lot of mistaken public and private areas within the conference center which results in disorientating the user and the production of unnecessary dead ends. Therefore public spaces have to be clearly indicated both by architectural layout and signage.

Hotspot 7: Stairways. Here lies the main disadvantage of the building. In architecture, a stairway should serve as visual focus and spatial connector. In the Heinrich-Lübke Haus they do not fulfill this criterion. In general, stairways should help integrating vertical information while exploring multilevel buildings and they should ease experiencing the layout spatially with respect to the building as a whole. Stairways are architectural design elements in their own right and not just technical components of the building for going up or down. They function as a significant circulation node as well as a vertical interconnection between different levels of the building and thus enable the movement flow between the levels of the building.

During vertical motion, well-designed stairways can provide access to various perspectives of the interior organization of the building and thus facilitate its legibility. Also, investing time into the design of stairways has yet another facet: Individual floor plans may be readily changed to suit specific tenant requirements, but the facilities for pedestrian circulation between the floors in the building are fixed.

Vertical circulation is one of the most important aspects of good building design in architecture. So, when planning the design of staircases architects generally have to take into account two key design parameters. First the constructional and representational form of its appearance have to be highlighted with respect to the function of the building and second the position of the stairway has to be optimized in relation to the user' s activity within the layout.

Ideally, stairways of a building represent its functional framework and accordingly, architects speak about the spatial nerve tract of the building (i.e., Vasari, 1946; Scamozzi, 1615). As we have discussed for Hotspot 1, the positions of the five small stairways in the conference center are not evenly dispersed and not perceptively placed (see Figure 8). Furthermore, there is no main stairway that functions as the user's visual focus while exploring the building. The frequently used stairway near the entrance hall is particularly counter-intuitively located (see Figure 1 & 8). Consequently, not only the impractical location of the entrance hall but also the stairway has a negative effect on the building's usability. Users do not readily perceive a main stairway to the upper floors.

Using the foremost stairway (near the entrance hall), there are a lot of spatial twists and turns without an opportunity for controlling one's location. This deficit is at least partly due to the complete lack of visual access to the outside, which would help to improve spatial updating. Additionally, the number of rotations within the stairway plays a great role for the user's stability of his cognitive map of the building (see Figure 9). As this staircase is offset from the main axis and not directly accessible from the entrance hall, a total of seven turns is necessary when moving between the main corridors of two levels. Frequently, users reported being very disoriented after using this stairway. Six of the seventeen episodes of getting lost (35%) are identified as disorientation observed directly after leaving the stairway, sometimes even before reaching the proper destination level. An

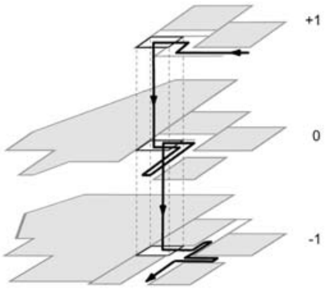

Figure 9: Closeup of the most central staircase, located closest to the entrance hall. The black line illustrates a participant's movement from level +1 to the basement, including path deviations related to disorientating properties of the stairways.

illustration of a typical episode of getting lost due to the stairway is illustrated in Figure 9.

Taken together, the analyses revealed that - except for global building characteristics - the staircases are the single most clearly identified cause of wayfinding problems in our setting. Further research into the consequences of rotations in vertical movement is clearly called for (see also Richardson, Montello & Hegarty, 1999).

6 Future Research

Providing guidelines for improving wayfinding friendliness and usability (Werner & Long, 2003) is clearly a practical goal of our research. For instance, the benefits of the floor strategy identified in the present experiment warrant further investigations. What are the specific factors that contribute to the familiar participants' preference for this strategy and what are the relationships to configurational features of the floor layouts. It also remains to be seen in further studies to what extent variations in task characteristics (e.g., goal concreteness) shape strategy preferences and performance in 3D settings. We will also need check whether the results of our study generalize to buildings with less complicated layouts across floors. It remains to be tested in subsequent studies, how the 3D navigation strategies are related to the important theoretical concept of "frame of reference" (cf. McNamara & Valiquette, 2004) in more detail. Werner & Long (2003) have provided a basis with their identification of local mismatches of reference frames in a building and this should be extended to the multi-level case.

Based on the present study we hope to intensify the cooperation of cognitive scientists and architectural designers. In the future, we will develop specific methods to support usability from the early planning stages on, in order to avoid costly design mistakes. Besides using virtual reality techniques for testing layout prototypes, we envision augmenting Space-Syntax-type layout analysis with the techniques presented here to identify usability deficits. Our study has demonstrated the general usefulness of verbal data for systematic statistical analyses of cognitive processes in wayfinding - at least if they are combined with objective wayfinding measures.

Helping to understand the cognitive strategies of building users is a valuable contribution of cognitive science to architectural planning.

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3.5 Schematic maps in wayfinding and self localisation

How much information do you need?
Schematic maps in wayfinding and self localisation

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Abstract: The paper is concerned with the empirical investigation of different types of schematised maps. In two experiments a standard floor plan was compared to three strongly schematised maps providing only route knowledge. With the help of one of the maps, the participants had to localise themselves in two tasks and performed two wayfinding tasks in a multi-level building they didn't know before. We recorded map usage time and a range of task performance measures. Although the map provided much less information, participants performed better in wayfinding with an unambiguous schematic map than with a floor plan. In the self localisation tasks, participants performed equally well with the detailed floor plan and with the schematised map versions. Like the users of a schematic map, users of a floor map presumably oriented on the network structure rather than on local geometric features. This allows them to limit the otherwise potentially very large search space in map-based self localisation. In both types of tasks participants looked at the schematised maps for a shorter time. Providing less than standard information like in a highly schematised map can lead to better performance. We conclude that providing unambiguous turning information (route knowledge) rather than survey knowledge is most crucial for wayfinding in unknown environments.

Keywords: schematisation – map – wayfinding – self localisation – route knowledge – survey knowledge – multilevel building

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1 Introduction

Maps are a common tool for orienting ourselves in our environment, may they come in paper form or be displayed on our mobile device. Comparing a paper hiking map with one displayed on a mobile device or a subway map the amount of information provided in those maps can vary tremendously. In the paper map you might see individual houses whereas in the mobile or subway map only the coarse direction of routes is displayed. The question of this study is how much information in a map is necessary, how much is superfluous? Is a highly schematised map sufficient for orientation or do we need further details? Does this depend on the goal we want to achieve with our map: Is a schematic map sufficient for finding our goal, but not for locating our current location after getting lost?

To address these questions we, first, review several theoretic approaches to schematisation. We, second, try to classify these approaches by the distinction of route and survey knowledge and identify the relevance of this knowledge from empirical studies. Third, we propose cognitive processes underlying wayfinding and self orientation with maps. From these assumptions we derive hypotheses predicting performance in wayfinding and self orientation for normal and highly schematised maps. Last, we test these predictions in two experiments and discuss the results with respect to the literature.

1.1 Theories of Schematisation

The question of what information is necessary for locating ourselves and finding our goals has found different answers. In cognitive science, this is often referred to as schematisation; the abstraction from unnecessary detail to concentrate on the essential information (e.g., Herskovits, 1998). For maps this involves omitting details e.g. the corner of a house or omitting dimensions e.g. colour information. We will introduce several approaches of schematisation. The reference point for all these approaches is the *topographic map*. In our terms a topographic map is a map which displays correct distances and angles between locations. Common hiking maps and also most city maps are topographic. It is important to notice that all maps, also topographic maps, do not display all spatial information available in our environment and therefore are schematic (Tversky, 2000). However, as metric relations are kept constant, a topographic map can be seen as a reference point to (more) schematised maps.

In a *topological map* only information about the network structure can be obtained. As a consequence a user located at B (see Table 1) can only determine to go into direction C, but not whether this implies turning right or left, as this information might not be displayed correctly in a map. Not knowing whether your path turns right or left is all right when taking the subway as your destination is written on a sign on the train, but it is beyond the pale for walking to your goal: Standing at an intersection the information of having to navigate to the city hall does not help at all, if you don't know in which direction to walk in order to do so. Consequently, mere topology can be sufficient for using a subway, but not for walking to our goal.

One approach to schematise maps comes from discrete curve evolution (Barkowsky, Latecki, & Richter, 2000). The shape of routes is simplified. Curvature between two locations is *straightened* (see Table 1). Local arrangements are to be kept constant. E.g. there is a house adjacent on the right side of the street. When the street is straightened the new position of the house should not be far away from the street, not on the street nor to the left of the street, but again on the right side adjacent to the street.

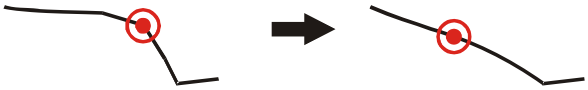
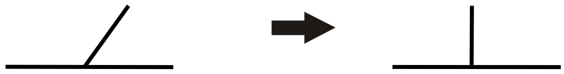
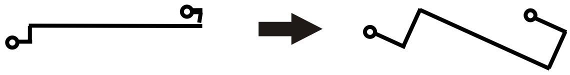
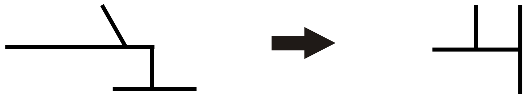
Schematisation principle	*Survey information*	*Route information*
Topologic map 	incorrect	incorrect
Straighten 	rather correct	correct
Categorise junctions 	rather incorrect	correct
Enhance relevant information 	start & goal correct	correct
Route knowledge map 	incorrect	correct

Table 1: Schematisation principles and pictorial examples for these principles. From a topographic, i.e., a metrically correct map (left of the arrow) a schematised map (right of the arrow) is derived. The amount of survey and route information preserved in the schematised map is roughly described in the columns on the right side.

Another approach to schematisation is to *categorise* the environment (Klippel, 2003). Categorisation doesn't include the whole continuum of a route, but is focused on only e.g. the intersections. These intersections can be categorised again by reducing the possible angles of two intersecting streets to, say, only 90° or 90° and 45° (see Table 1). Especially for route maps which provide information about how to get from the start to the goal this is a feasible approach. In a second step it is also possible to cluster intersections (Richter & Klippel, 2005). E.g. if you have to turn right at a T-intersection you could omit all intersections before the T-intersection where you have to walk straight, like we often do in verbal directions like "at the T-intersection turn right".

Another route map approach for cars is based on the principle to *enhance relevant information* and reduce or remove irrelevant information (Agrawala, & Stolte, 2001). Most often when driving a car we have to cruise around several streets to reach a highway. Then we cover most of the distance on this highway before cruising again small streets in order to reach our goal. In a topographic map most parts will be occupied by the long highway. This approach enlarges the important parts of the map at the start and at the end of the route and shrinks the long distances on a highway (see Table 1). In doing so, the relative location of the goal with respect to the start is kept constant.

There is no general theory of schematisation yet (cf. Klippel, Richter, Barkowsky & Freksa, 2005). All approaches omit certain information from the environment. This involves the curvature of a segment (straighten & enhance information), the length of a segment (enhance information), exact angles at branching points or even streets not necessary on a specific route (categorise junctions). As a consequence the exact metric locations displayed on a map, which provide so called survey knowledge, are distorted to a smaller (straighten) or stronger extent (categorise junctions) or do not provide meaningful information at all, as in the case of a topological map (see Table 1). We will review the importance of survey knowledge and its counterpart route knowledge in the next section.

1.2 Route and Survey Knowledge in Schematised Maps

The distinction between route and survey knowledge is fundamental in spatial orientation research (e.g., Siegel & White, 1975). Route knowledge includes knowledge about a series of actions that have to be taken in order to reach the goal independent from knowing the exact position of the goal, e.g. turn right at the church, then the second street to the left. Survey knowledge on the other hand includes knowledge about the direction and distance between locations independent from knowing a path that leads there, e.g. the train station is about 300 Meters east from here.

Previous research strongly suggests that route knowledge is the crucial factor in finding your goal: In our daily life we recall route knowledge rather than survey knowledge. About 80% of all mentioned descriptions in verbal directions are concerned with actions and landmarks (Denis, 1997). People very familiar with an environment have been shown to express only little survey knowledge of this environment (e.g. Moeser, 1988). For reaching a goal in cities and buildings, survey knowledge was shown to play only a minor role (Hölscher, Meilinger, Vrachliotis, Brösamle & Knauff, 2005; Meilinger & Knauff, submitted). Orienting on survey relations could even be detrimental for performance (Meilinger &

Knauff, submitted). Topographic maps displaying route *and* survey information have been found to provide no additional help in wayfinding compared to signs which only display route information (Butler, Acquino, Hissong, & Scott, 1993; Hölscher, Büchner, Meilinger & Strube, in press) or to verbal directions not providing survey information (Meilinger & Knauff, submitted; Schlender, Peters & Wienhöfer, 2000). So at least for wayfinding route knowledge seems fundamental, whereas survey knowledge can be omitted.

Transferring these results to schematic maps, one could think of a map only concentrating on providing correct route knowledge while omitting all survey knowledge. For our experiment we constructed such a schematic route knowledge map and compared it to a topographic map additionally providing survey knowledge. In constructing such a map (see bottom row of Table 1), we applied two principles: (1) Each junction in the map was connected to the closest junction by a straight line of normalised length, no matter whether the real distance was 5 or 50 meters. Mere turns between intersections were not considered. When walking between two junctions multiple changes in direction could occur. (2) All angles at junctions were changed to 90° or 180° angles. A turn to the right remained a turn to the right, but the turning angle in the map was always 90°. Local orientation of junctions in the map was correct. A T-intersection in the map always corresponded to a T-intersection in reality, a turnoff in the map always to a real turnoff, although the exact angles between streets might have differed. Despite the topologic network structure, only the local orientation of intersections was represented in such a map. The map was metrically incorrect. Route information was preserved: at any point the participant was able infer from the map whether to turn left, right or walk straight on in order to reach the next junction. Contrary to that survey information was omitted: no correct inference regarding distances and overall orientation could be drawn.

1.3 Wayfinding and Self Localisation with Schematised Maps

Starting from empirical findings we described two principles for constructing a strongly schematised map, which we compared to a standard topographic map. The basic idea is that the schematised map is sufficient for orientation, despite providing much less information compared to the topographic map. Does this hold true for all spatial orientation tasks? In the following we differentiate between finding a goal and localising oneself e.g. after getting lost. We propose that for wayfinding a schematised map is sufficient, whereas for self localisation participants lack important information and therefore should perform worse.

Wayfinding. When we want to reach a goal using a map, we usually know our current location and the location of our goal. Following Passini (1992) we assume three steps in solving the wayfinding problem. The steps can be iterated several times:

Planning. The first step is planning a route from the start to the goal (or the general area of the goal) in the map. We could encode or learn the whole map, throw it away and plan the route based on our representation of the map. It has been shown, however, that planning is much easier using external representations like a map than using our own internal representations – possibly one reason why maps exist (Scaife & Rogers, 1996).

Transformation and encoding. When we have settled for one route, we have to encode, i.e., memorise the route. Only very few people walk around looking constantly at the map. Even if they do so, they have to transform the information from the map in order to use it for moving around. This transformation involves aligning the map mentally or physically with the environment so that "up" in the map corresponds to "forward" in the environment (e.g. Levine, Jankovic & Palij, 1982). For a transportable map, this could be accomplished by rotating the map. The transformation, however, also involves a perspective switch from the top down perspective of the map to the ground-level (egocentric) perspective in which we encounter the environment (e.g., Shelton & McNamara, 2004). As our memory capacities are limited we probably won't encode the whole route, but only a part of it and start with this.[1]

Walking and monitoring progress. After transforming and encoding the map, we use our internal representation to guide our locomotion. E.g. we walk straight on to the next intersection and turn left there. In doing so we have to monitor our progress, i.e., to mach our internal representation e.g. of an intersection with our environment, before executing a behaviour e.g. turning left and then access the information of what to do next and where. Matching locations of the environment with corresponding internal representations helps us with monitoring our progress, identifying our goal and keeping us oriented. When we reach the end of the memorised (sub-)path and/or feel unsure, we look into the map again and go back to the planning stage or to encoding and transforming the upcoming part of our already planned route. When making a mistake (or using an erroneous map) we can get lost, i.e., our actual location does not correspond to our assumed location in the map or in the representation formed from it. After that, we have to localise ourselves again, before being able to plan, encode and execute a new route. Self localisation will be described in the next section.

We described our assumptions regarding the process of wayfinding using a map. Within this model alternative strategies can be imagined. Our examples described a route strategy which includes a one dimensional string of actions at decision points. However, also a survey or least angle strategy is possible (Hochmair &

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[1] The transformation process can also happen online during walking the route. For this, the map would need to be encoded beforehand. Again as argued for planning we assume that the transformation is much easier, when having access to the external representation of the map, than when having to rely on an internal representation of the map.

Frank, 2002; Hölscher et al., 2005). This strategy includes identifying the direction and distance to a (sub-)goal (planning), encoding and transforming this into a horizontal perspective and trying to walk directly to this spot (walking and monitoring progress). The survey strategy is only applicable using a topographic map as the route knowledge map does not provide correct survey information.

Taking this model of wayfinding we assume that the schematised map provides sufficient information for all stages of the wayfinding process applying a route strategy. As lots of detail information is missing we predict that the planning, encoding and transformation process could be performed faster and less error prone than with a topographic map. Participants therefore should be quicker in consulting the map. For wayfinding itself we assume that participants with a schematised map perform at least as good as participants with a topographic map although the topographic map provides much more information.

Self localisation. When we are disoriented, i.e., when we do not know where in relation to our memory or a map we are, we try to localise ourselves. To regain our orientation in an unknown environment we have to *compare features of our surrounding with features of a map* (e.g., Warren, 1994). For example, when standing at a T-intersection we can search for all T-intersections in the map. Based on the individual geometry of our T-intersection we might distinguish this T-intersection from other T-intersections. In doing so, we localise ourselves using *local cues* which are visible from our current location. These cues could be the geometry, or landmarks displayed in a map e.g. churches, street sizes or doors in the map of a building. The literature on self localisation is very much focused on such local cues and emphasises the importance of geometric features (e.g., Hermer-Vasquez, Spelke & Katnelson, 1999). In contrast we can also orient on the *network structure* of our surrounding, i.e., only taking decision points into account, e.g. "if I am here in the map, then there should be a T-intersection straight ahead and a crossroads to the left". Localising on local cues or on the network structure is probably best described as a hypothesis testing procedure, i.e., we generate a hypothesis about our current location and try to confirm or reject this hypothesis by collecting more information.

Our experiments took place in a multi-level building. Compared to single layer spaces like cities, the relation and representation of multiple layers poses difficulties. Humans have trouble correctly aligning vertical spaces in pointing tasks (Montello & Pick, 1993). Soeda, Kushiyama and Ohno (1997) observed wayfinding performance in tasks involving vertical level changes. They found people losing their orientation due to vertical travel, supporting more informal results of Passini (1992).

Our schematised map only preserves the network structure of the environment and the raw layout of intersections e.g. T-intersections, but lacks exact local geometry. As geometry is considered an important cue for self localisation

(Hermer-Vasquez, Spelke & Katnelson, 1999), we assume participants to localise better if using a topographic map which preserves geometry.

1.4 Hypotheses

We proposed a map schematisation approach providing route knowledge and omitting survey knowledge. Such a highly schematised map was compared to a standard topographic map additionally providing information about survey relations as well as local geometry. Due to local geometry which was shown to be important in self localisation, we predicted that participants with a topographic map would perform better in localising themselves. Due to the central importance of route knowledge for wayfinding, we predicted that participants with a schematised map would perform at least as good as participants with a topographic map. This would be despite the fact that the topographic map provides much more information. Due to the sparser information in the schematic map, we predicted that participants would be faster in encoding information from the schematic map than from the topographic map. This was expected in both types of tasks, wayfinding and self localisation.

In Experiment 1 we compared a topographic map, i.e. a floor plan of a multilevel building with our highly schematised map. In Experiment 2 we investigated the relevance of ambiguity, an issue which occurred in Experiment 1, with a set of two new schematized maps. Conducting both experiments with the same tasks and in the same setting allowed us to compare results between the experiments.

2 Experiment I

2.1 Methods

Participants were asked to participate in two self localisation tasks. They had to locate the position in a map corresponding to their actual position in a building unknown to them. They also performed two wayfinding tasks in the same building. For this they were shown their actual position in the map and had to find a goal also shown to them on the map. All tasks were either conducted with a topographic floor plan or with a highly schematised map.

Participants. Participants were attendees of an annual summer school for human and machine intelligence which takes place at a conference centre in Günne, near Düsseldorf, Germany. They were recruited from the list of participants of the summer school via e-mail, before the event started. 5 women and 13 men agreed to participate in the experiment. The participants were at the end of their twenties ($M = 28.6$; $SD = 5.7$), all were native German speakers.

Material. The conference centre was built in 1970 (see Figure 1). It consists of four floors connected with five staircases. Its complexity causes many visitors to get lost. For further discussion of the building see (Hölscher et al., 2005).

The participants either got a floor plan or a schematised map for the task. In the *floor plan* each level of the building was seen from birds eye view (see Figure 2 left side). Symbols for staircases were added and connected with dashed green lines. The metric distances in the floor plan were correct. Doors were not displayed. Participants were not allowed to enter rooms. The display of rooms enabled participants to judge the outlines of the building.

The schematic or *simple map* (Figure 2 right side) was derived from the floor plan following the principles described in 1.2. Each junction and staircase (node) in the map was connected to the closest staircase or junction (node) by a straight line of normalised length. Turns between nodes were ignored, except for one turn in the square in the middle of the basement, where this was not possible. All angles at junctions were changed to 90° or 180° angles. In comparison to the floor plan, the simple map provided route knowledge and omitted survey knowledge. Turning

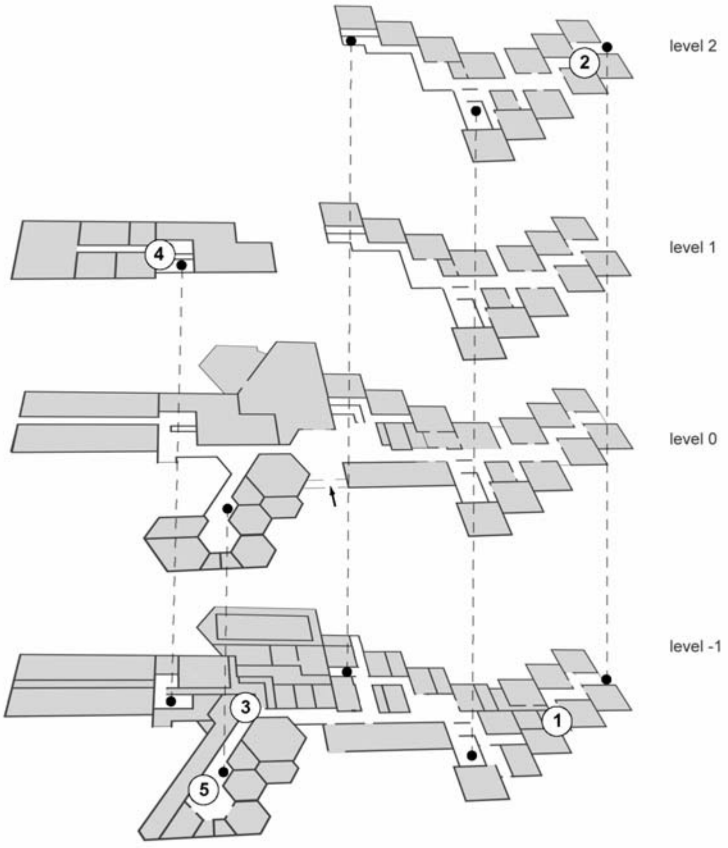

Figure 1: The conference centre where the experiment took place. Starting points for the self localisation tasks (number 1 and 4) are shown. In the wayfinding tasks the participants had to walk from number 2 to 3 and from number 4 to 5. The numbers correspond to the order in which all tasks were performed.

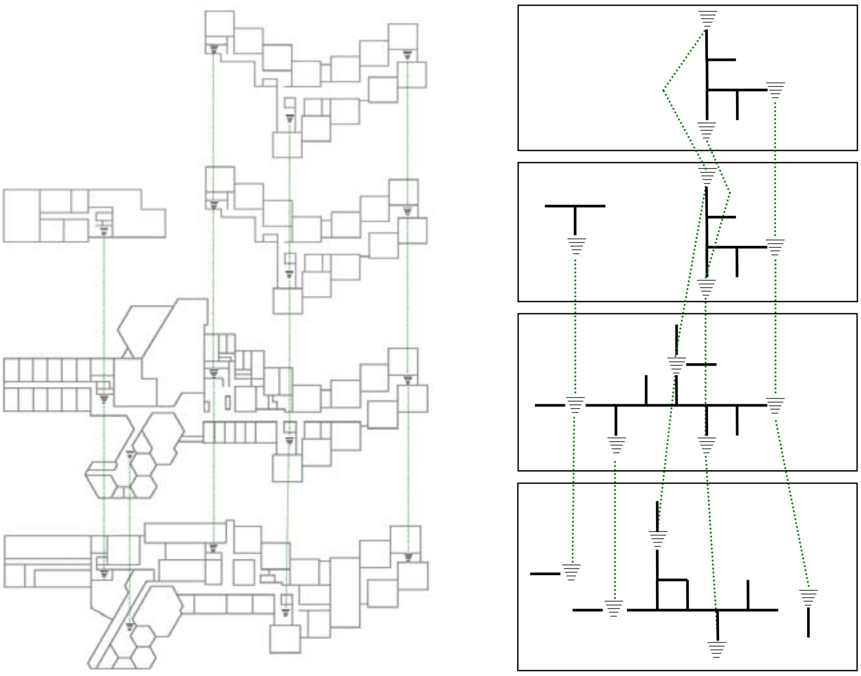

Figure 2: The floor plan on the left and the schematised "simple" map on the right. Corresponding staircases on different floors are connected with green dashed lines.

information was correct, but distance and global orientation information were not to be relied on. Despite the topologic network structure of nodes, only the local orientation of intersections was represented in the simple schematised map. Both floor plan and simple map were presented on an A4 paper (29.7 cm x 21 cm) in an opaque folder which had to be opened in order to see the plan or map.

Procedure. The participants performed two *self localisation* tasks. They were taken to the starting points blindfolded (number 1 and 4 in Figure 1). In order to reach the start of the first task they entered the building from outside. They were able to guess that they were on the ground floor or in the basement. For the second task they were also disoriented and brought to the correct floor via corridors only accessible to staff and by an elevator starting from the basement. They could, therefore, infer not being in the basement any more. The participants' task was to locate themselves in the map, i.e. to show their actual position on the map. For this they were allowed use the map and walk around, but not both at the same time. The experimenter instructed them to only answer when they were certain and not simply to guess where they were.

For the two *wayfinding* tasks the experimenter brought the participants to the starting point without blindfold (number 2 and 4 in Figure 1). He showed them their current position in the map and their goal. In the building the goals were marked with a red square on the floor (number 3 and 5). The participants had to find the goal as quickly as possible while moving with normal walking speed.

The participants started with the first self localisation task (number 1) followed by the first wayfinding task (from number 2 to 3). These tasks took place in the *large* *area*: For the self localisation task it was necessary to more or less consider the whole building as their possible actual location. In the wayfinding task they covered about ⅔ of the building. After the tasks in the large area they performed a self localisation and a wayfinding task in the *small area*. In the self localisation task (number 4) the participants could exclude the parts of the building already known to them reducing the number of available alternatives. The adjacent wayfinding task (from number 4 to 5) covered only about ⅓ of the building and was therefore much shorter than the first wayfinding task.

The participants were videotaped. From the video we derived the following dependant measures:

- *Time* to complete the task, taken from the video. Extra time, e.g., stops with explanations because of experimental issues was subtracted
- Distance covered
- *Detours* to locations visited before (only in wayfinding tasks)
- *Average detour distance* per detour (only in wayfinding tasks)
- *Map usage:* Number of stops to use map (participants were asked only to use the map while standing)
- *Average map time* per map usage, i.e., average time between opening the folder containing the map and closing it again.

Two experimenters conducted the tasks in parallel. During the experiment the participants were asked to verbalise their thoughts. They also accomplished two pointing tasks before and after the second wayfinding task (at number 4 and 5 in Figure 1). Pointing and verbalisations are beyond the scope of this paper and therefore reported in a later publication. One participant in the floor plan condition had to be excluded due to not being able to complete the tasks. The assignment of participants to experimental conditions was controlled with respect to gender and experimenter. Parameter values deviating more then three standard deviations from the overall mean were replaced by the most extreme value observed inside three standard deviations. We computed independent t-test to compare between maps, gender and experimenter. Since nonparametric U-tests revealed very similar results only the more common parametric t-tests are reported.

2.2 Results

The results did not differ due to experimenter (all 20 $t(16) < 2.1$, $p > .096$, $d < 0.87$). The data was therefore collapsed for further analysis.

Self localisation. In the large area participants with a floor plan looked per stop twice as long at their plan than participants with the simple map (see Table 2 left

	Experiment 1		*Experiment 2*	
	Floor plan	*Simple map*	*Comb map*	*Square map*
Large area				
Time [s]	352 (240)	330 (218)	246 (82)	236 (99)
Distance [m]	87 (112)	116 (59)	80 (31)	66 (23)
Map usage [n]	4.7 (4.7)	6.0 (4.0)	4.6 (0.7)	4.1 (1.5)
Av. map time [s]	*65 (36)*	*32 (16)*	36 (17)	40 (15)
Small area				
Time [s]	106 (63)	100 (49)	165 (90)	141 (55)
Distance [m]	10 (10)	18 (15)	31 (13)	22 (17)
Map usage [n]	2.3 (1.0)	2.1 (0.8)	3.1 (1.4)	2.8 (1.3)
Av. map time [s]	31 (16)	39 (41)	37 (22)	35 (9)

Table 2: Average performance in self localisation for Experiment 1 and 2. Means and (standard deviations) are shown. Means displayed in italics differ in direct comparison at $p < .05$.

	Experiment 1		*Experiment 2*	
	Floor plan	*Simple map*	*Comb map*	*Square map*
Large area				
Time [s]	305 (144)	264 (128)	286 (65)	266 (85)
Distance [m]	183 (62)	159 (28)	153 (17)	139 (23)
Detours [n]	1.8 (1.5)	1.2 (0.8)	1.0 (0.7)	0.3 (0.7)
Av. detour dist. [m]	25 (18)	20 (21)	21 (10)	22 (2)
Map usage [n]	5.3 (3.9)	5.4 (2.2)	6.6 (2.1)	4.9 (1.5)
Av. map time [s]	28 (7)	24 (21)	21 (10)	25 (11)
Small area				
Time [s]	143 (76)	165 (52)	191 (164)	199 (125)
Distance [m]	66 (18)	94 (35)	81 (25)	86 (31)
Detours [n]	0.9 (1.4)	1.6 (1.1)	1.0 (0.5)	1.4 (1.5)
Av. detour dist. [m]	*10 (4)*	*24 (9)*	18 (13)	14 (7)
Map usage [n]	3.1 (1.8)	4.4 (1.3)	4.9 (2.0)	4.9 (1.7)
Av. map time [s]	*26 (12)*	*14 (8)*	16 (10)	19 (10)

Table 3: Wayfinding performance in Experiment 1 and 2. Means and (standard deviations) are shown. Means displayed in italics differ in direct comparison at p < .05.

side, $t(11.0)$[2] $= 2.57$, $p = .026$, $d = 1.21$). We did not find any further significant differences regarding self localisation neither in the large nor the small area (all seven $t(16) < 1.22$, $p > .243$, $d < 0.61$). No *gender* differences in self localisation performance were found (all eight $t(16) < 1.15$, $p > .270$, $d < 0.62$).

Wayfinding. In the *small area* participants with a floor plan performed better than participants with a simple map (see Table 3 left side). Their average distance of detours was smaller ($t(10) = 2.67$, $p = .024$, $d = 1.86$). There was also a trend to stop

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[2] Both experimental groups differed in their variance. The degrees of freedom were therefore adjusted from 16 to 11.0)

less often ($t(16) = 1.77$, $p = .097$, $d = 0.83$) and cover less distance ($t(16) = 2.07$, $p = .055$, $d = 0.98$). When using the floor plan they, however, stopped for longer times than participants with a simple map ($t(16) = 2.64$, $p = .018$, $d = 1.24$). The groups did not differ significantly with respect to time or number of detours ($t(16) < 1.13$, $p > .276$, $d < 0.54$). In the *large area* participants with a simple map performed numerically better. These differences, however, never reached the level statistical significance (six $t(16) < 1.08$, $p > .300$, $d < 0.51$). Wayfinding performance did not differ due to *gender* (all twelve $t(16) < 1.84$, $p > .078$, $d < 1.33$).[3]

2.3 Discussion

When using their maps, participants with the floor plan looked longer in the map than participants with the simple map – both in wayfinding and in self localisation. Consistent with our predictions they encoded more information from the floor plan or they needed more time to extract the relevant information from the floor plan.

For *self localisation* we predicted a better performance in participants with a floor plan. Only the floor plan not the schematic map provided local geometry which was considered an important cue in self localisation. Contrary to our prediction both groups performed equally well in localising themselves. The performance measures did not even show a consistent numerical advantage for the floor plan, excluding a lack of statistical power as an explanation. We conclude that both groups mainly used the network structure available in both maps for localising themselves. Why was that? Using local geometric features might offer too many opportunities to look for in the floor plan. E.g. there were a lot of bends in a corridor to check for in the map. Focusing on nodes in the network structure instead reduced the possible search space to a reasonable size. Fewer hypotheses had to be tested and kept in memory.

For *wayfinding* we expected participants with the simple schematic map to perform at least as good as participants with the floor plan. Despite containing much less information, the schematic map should provide the relevant information for wayfinding. While participants using the simple map performed numerically better in the large area, participants using a floor plan performed better in the small area. Why did they perform better in one task? We assume that the simple schematic map provided ambiguous turning information after floor changes. After walking down the stairs, participants with the simple map could not know whether they should turn left or right next. Participants with a floor plan could disentangle this ambiguity by local geometric features e.g. the form of a

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[3] Due to unequal group sizes and adjustment of the degrees of freedom to account for unequal variances, some rather large effect sizes in favour of men did not become significant.

corridor. Indeed in the small area task almost all detours using the simple map had their origin after exiting stairs. In the large area task no ambiguity occurred, as all stairs were located at the end or very close to the end of a corridor. Here, no advantage of the floor plan was observed. In order to address this problem we conducted a second experiment in which we varied the ambiguity of two schematic maps.

3 Experiment II

3.1 Methods

The goal of this experiment was to determine the influence of ambiguity in schematic maps. In the simple schematic map of Experiment 1 we identified an ambiguity for participants after floor changes. Especially in the small area participants could not know from the map which direction they had to go when exiting stairs. To disentangle this ambiguity we placed the symbols for staircases to the side of a corridor and oriented them facing the direction towards the corridor (see Figure 3 right side). Also the lines connecting floors via the staircases were changed and entered the stair from the back additionally indicating ones orientation when exiting a staircase. For the ambiguous map the staircases and connections between the floors were the same as in the simple map of Experiment 1 (see Figure 3 left side). Additionally the structure of intersections was changed

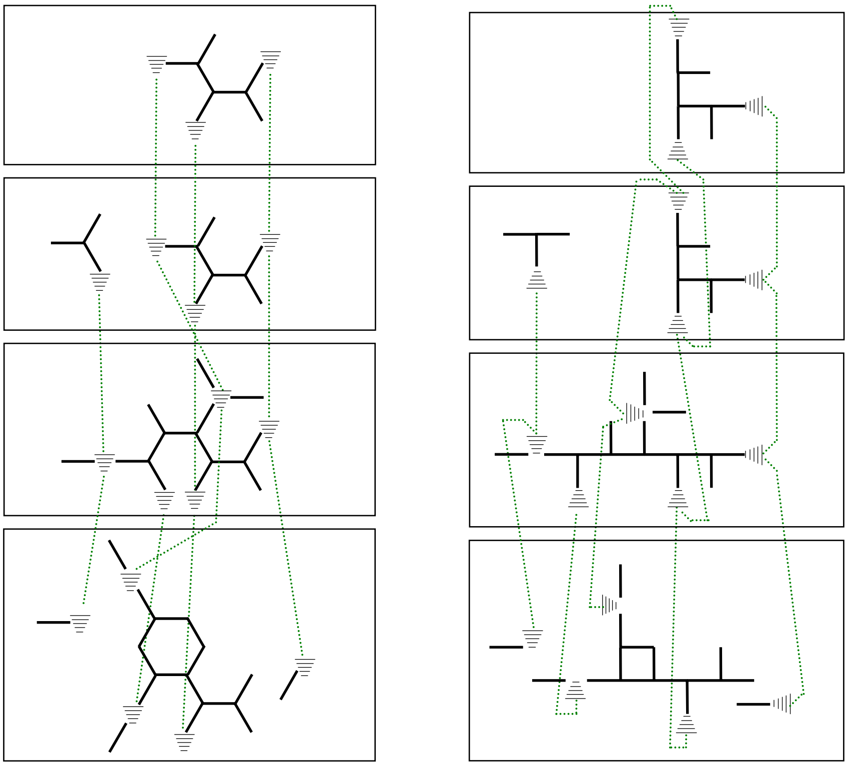

Figure 3: The maps used in Experiment 2. On the left side the ambiguous “comb map”, on the right side the unambiguous “square map”.

from 90° angles to 120° angles in order to provide two path alternatives branching off at the same angles. At an intersection the map always provided a left and a right alternative, no matter whether in the building this was a T-intersection or a corridor branching off to the left. In the later case the main straight corridor was indicated in the map not with a straight corridor, but with a turn to the right. Due to its honeycomb structure we called this map "comb map". In contrast to that we called the unambiguous map "square map".

The experiment took place at the same annual summer school as Experiment 1 one year later. Nine women and nine men agreed to participate in the experiment. Again, the participants were around the end of their twenties ($M = 27.4$; $SD = 12.6$) and spoke German fluently. One participant in the square map condition not reported here had to be excluded due to not being able to complete the tasks. The selection and assignment of participants, the tasks, procedure, instruction and data analysis were identical to Experiment 1.

3.2 Results

Except for detours in wayfinding in the small area ($t(16) = 2.39$, $p = .029$, $d = 1.13$), the results did not differ with respect to experimenter (all 19 $t(16) < 1.51$, $p > .150$, $d < 0.60$). No different results were obtained when including the experimenter in the analysis of this parameter. Therefore, only the collapsed data are reported.

Self localisation. The participants performed equally well in localising themselves, no matter whether they used the comb map or the square map (see Table 2 right side, all eight $t(16) < 1.24$, $p > .236$, $d < 0.59$).

In the small area women outperformed men. They were faster (109s vs. 197s, $t(16) = 3.12$, $p = .007$, $d = 1.47$), covered less distance (15m vs.. 37m, $t(16) = 4.17$, $p = .001$, $d = 1.96$) and used the map less often (2.2 vs. 3.7, $t(16) = 2.78$, $p = .014$, $d = 1.31$) before correctly localising their position. Women and men did not differ in time per stop or in the in the large area (all five $t(16) < 1.27$, $p > .224$, $d < 0.60$).

Wayfinding. Participants with the comb map and the square map did not differ in their general wayfinding performance (see Table 3 right side). In the large area there was a trend for participants with the square map to make less detours ($t(16) = 2.0$, $p = 0.63$, $d = 0.94$) and use the map less often ($t(16) = 1.94$, $p = .070$, $d = 0.91$; all ten other measures $t(16) < 1.42$, $p > .176$, $d < 0.68$). Wayfinding performance did not differ with respect to gender (all twelve $t(16) < 1.84$, $p > .302$, $d < 0.51$).

3.3 Discussion

Participants with the ambiguous comb map and participants with the unambiguous square map did not differ in localising themselves. As in Experiment 1 this findings indicate that the network structure was the main source of information used for self localisation. Unambiguous local intersections and staircases only provided in the square map did not lead to a significantly better performance. Local unambiguousness did not play a crucial role in these tasks.

We do not have an explanation for the better performance of women in self localisation. This did not occur in Experiment 1 where there were no significant differences, men even performed numerically better. Generally, men are known to perform slightly better than women in spatial orientation tasks (for a recent review see Coluccia, & Louse, 2004). For the wayfinding tasks used in Experiment 1 and 2 which were the same as tasks used in another experiment (Hölscher et al., 2005) no advantage for women was observed.

We did not observe any significant differences in wayfinding performance with respect to the maps. There was a trend for participants in the large area to perform better with the unambiguous square map. With nine participants per group this difference, however, did not reach the level of significance. Ambiguity could therefore *not* be a crucial factor for wayfinding with schematic maps. A minor importance of ambiguity could, however, not be ruled out. To see how participants with ambiguous *and* unambiguous schematic maps perform in relation to a floor plan we compared the results of Experiment 1 and 2.

4 Comparison of Experiment I and II

4.1 Methods

In order to compare a floor plan with ambiguous and unambiguous schematic maps over both experiments we used three groups: a) The floor plan, b) the unambiguous square map and c) the two ambiguous schematic maps, consisting of the simple map from Experiment 1 and the comb map from Experiment 2. We compared these three groups using a one-way ANOVA with pair-wise planned contrasts between the groups when an overall difference was observed. Especially the contrast between the floor plan and the unambiguous square map was of interest as the other two contrasts were partially contained in the data already presented in section 2 and 3.

4.2 Results

Self localisation. In the *large area* the time participants looked at the map per stop differed as a function of the kind of map (see Figure 4 left side $F(2, 33) = 6.07$, $p = .006$; $\eta^2 = .27$). Participants with a floor plan looked longer at the map compared to participants with schematic maps (floor plan vs. ambiguous maps: $t(33) = 3.45$, $p = .002$, $d = 1.14$; floor plan vs. unambiguous square map see also Table 2 outer columns: $t(33) = 2.41$, $p = .022$, $d = 0.93$). In the *small area* there was a trend for the participants to differ in the distance covered before locating oneself ($F(2, 32) = 2.62$, $p = .088$; $\eta^2 = .14$). Here participants with a floor plan covered less distance compared to participants with ambiguous maps ($t(32) = 2.26$, $p = .031$, $d = 1.11$; two other contrasts: $t(32) < 1.67$, $p > .106$, $d < 0.86$). We did not reveal any further reliable differences in other parameters (six $F(2, 33) < 1.0$, $p > .380$, $\eta^2 < .06$).

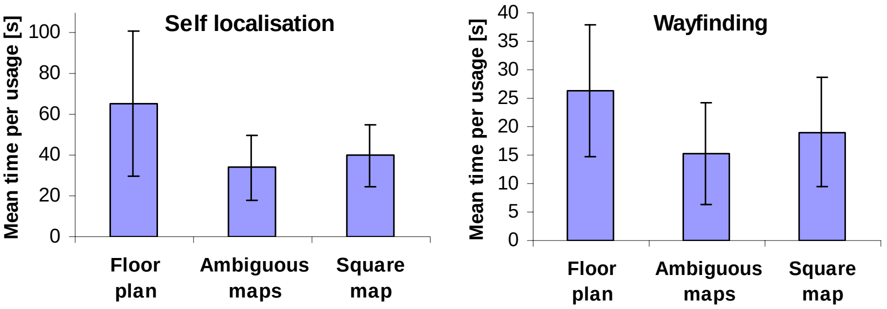

Figure 4: Mean time of map usage in participants with the floor plan, ambiguous maps and the unambiguous square map in both experiments. Means and standard deviations are displayed for self localisation in the large area (left side) and for wayfinding in the small area (right side).

Wayfinding. In the *large area* task participants differed in the number of detours ($F(2, 33) = 5.0$, $p = .013$, $\eta^2 = .23$) and the distance covered ($F(2, 33) = 3.31$, $p = .049$, $\eta^2 = .17$) as a function of the kind of map they used (see Figure 5). Participants with the unambiguous square map performed better than participants with the floor plan (detours: $t(33) = 3.14$, $p = .003$, $d = 1.24$; distance $t(33) = 2.54$, $p = .016$, $d = 0.93$, four other contrasts: $t(33) < 1.96$, $p > .059$, $d < 1.06$). We observed no further differences in the four other parameters (all $F(2,33) < 0.61$, $p > .553$, $\eta^2 < .04$).

In the *small area* task the participants differed in the time of their average map usage (see Figure 4 right side, $F(2, 33) = 3.87$, $p = .031$, $\eta^2 = .19$). Participants with ambiguous schematic maps looked shorter at their maps than participants with the floor plan ($t(33) = 2.78$, $p = .009$, $d = 1.08$; two other contrasts $t(33) < 1.59$, $p > .122$; $d < 0.70$). There was a tendency for floor plan users to stop less often compared to participants with schematic maps ($F(2, 33) = 3.14$, $p = .056$, $\eta^2 = .16$). We observed no differences in the other four parameters (all $F(2, 23/33) < 2.44$, $p > .109$, $\eta^2 < .18$).

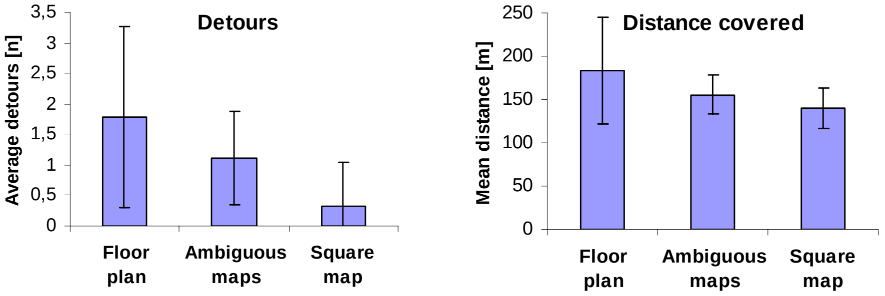

Figure 5: Wayfinding performance in participants with the floor plan, ambiguous maps and the unambiguous square map in the large area compared over both experiments.

4.3 Discussion

Participants with an unambiguous schematic map performed better in *wayfinding* than participants with a floor plan. In the large area task they made less detours and covered shorter distances. Despite its lower information content, using an unambiguous schematic map can lead to better performance than using a floor plan. This result is consistent with our prediction.

Why can it be better to use a schematic map? Time for planning and encoding alone could not be the reason. Participants looked at the schematic maps for shorter times, but this could only influence the overall wayfinding time and could not explain the fewer errors, i.e., fewer detours and the less distance covered. We assume that participants either encoded better information in concentrating on route knowledge or that they applied a better strategy, i.e., a route strategy. The schematic maps were constructed to provide only correct route knowledge which was shown to be central to wayfinding (see section 1.2). From such a map a user could learn where to turn at an intersection, but a user could not learn survey knowledge as distances and directions between locations on the schematic map did not correspond to the real distances and directions in the building. This fact was known to the participants. They were thus forced to encode and use only route knowledge. In contrast, participants with a floor plan could also encode survey knowledge or even local geometry. This information was less useful for the task (see section 1.2). Considering that memory capacity is limited, concentrating on relevant information should lead to fewer errors and therefore less detours and less distance covered.

The survey information from the floor plan might, however, not just distract from the more relevant route knowledge, it also enables the application of a survey strategy (Hochmair & Frank, 2002; Hölscher et al., 2005). Within a floor a participant could encode only the direction and distance of a (sub-)goal and try to walk there directly. In doing so, a route not leading to the (sub-)goal could be chosen resulting in more detours and distance covered. Although the survey strategy needs very little information to be transformed and encoded from the map, the encoded vector pointing to the (sub)goal has to be updated constantly. Consequently, the survey strategy implies a higher memory load during walking through the building which also could lead to more errors. With the route strategy the turning information at decision points had to be transformed and encoded from the map and maintained until it was used, but nothing had to be updated. So the memory load for the route strategy was high only during transforming and encoding when participants could use the map as an external representation to ease their tasks (Scaife & Rogers, 1996). Further research has to clarify whether the advantage of a schematic route-knowledge map stems from applying a different strategy or rather from a memory effect, e.g., not encoding irrelevant survey information or additionally relying on verbal memory to encode route knowledge. In the comparison of route and survey knowledge it might also be interesting to produce a map only providing survey knowledge and no route knowledge. Such a map would include the correct topographical location of decision points, but connecting paths would not be visualised. But very likely such a map would be practically useful only for navigation tasks in open terrain, not for indoor environments.

One factor in route knowledge is ambiguity. Route knowledge should be unambiguous. We did not find any significant differences when varying ambiguity in the second experiment. Maybe our variation was not strong enough. If we had used a topological and therefore a completely ambiguous map for comparison, we probably would have found stronger effects. However, when comparing the floor plan to the schematic maps only the contrasts to the unambiguous square map became significant. Ambiguity, therefore, has to be relevant in some way, although other factors might be more central.

Consistent with our prediction, participants needed less *time for encoding* information from a schematic map than from a floor plan. This holds true for both self localisation and for wayfinding. With less information provided in the schematic maps, participants are limited in the amount of information to encode. Additionally, they do not have to search for the relevant information within irrelevant information.

In *self localisation* no general advantage of the floor plan compared to schematic maps could be revealed. There was a trend for participants with the floor plan to cover less distance. This, however, only holds true for comparing floor plans with ambiguous schematic maps. No reliable difference or even trends between floor plan and the unambiguous square map could be revealed. We conclude that most participants relied on the network structure rather than the geometric layout. Searching the floor plan for locations with a specific geometric layout probably offered too many possible alternatives. Limiting the search space to easily identifiable configurations of nodes like intersections and staircases reduced the number of possible alternatives to a reasonable amount that can be handled by humans. The higher importance of network structure over geometry stands in contrast to results from self localisation studies which emphasise the importance of geometric features (e.g., Hermer-Vasquez, Spelke & Katnelson, 1999). There are, however, substantial differences between these studies and our experiment: Our participants had to localise themselves in an unknown environment using a map providing an *external representation*. In research on self localisation participants most often had seen the environment before and judged their current location based on their memories of this environment which are *internal representations*. A further difference besides internal vs. external representations is the kind of space the experiments took place in. In most self localisation experiments only room sized environments were used. According to Montello (1993) these spaces can be called *vista spaces* as all the space is visible from one point of view which also holds true for open places or even small valleys. Contrary to that, to understand *environmental spaces* we have to move around and take several views of the space into account which is the case for towns or buildings like in our experiment. So at least the kind of space (vista vs. environmental space) and the representation system on which the self localisation task was based (internal vs. external) differ between our experiment and most self localisation studies. Identifying, which factor or combination of factors do in fact cause participants to localise on the *network structure* rather than on *geometry* is subject to future research.

When comparing *gender* over both experiments (not shown) we did not observe significant differences like in Experiment 2. Reliable differences of any kind should be even stronger when comparing more participants. We, therefore, do not think that the gender differences observed in Experiment 2 should be emphasised too much.

5 General Discussion

Despite containing much less information, using a highly schematic map can lead to better wayfinding performance than using a topographic floor plan. Providing unambiguous route knowledge is central for this performance benefit. Self localisation with such a map is generally at least not worse than with a floor plan. Like the users of a schematic map, the users of floor map orient on the network structure rather than on local geometric features which would imply a very large search space. Both in wayfinding and self orientation participants are faster to encode information from the schematised map.

How do these results generalise to other situations and maps? All significant results in this study are based on large effect sizes with respect to Cohen (1988). In this field experiments we are not dealing with a highly artificial laboratory effect only observed under very specific conditions. The practical application for the results in self localisation will, however, be limited. In many maps today our current location is already marked, e.g. when using a wall-mounted you-are-here-map or a GPS-based system. For an old fashioned city map we often localise using street names or landmarks rather than comparing the network structure of our surrounding with the one in our map. Also the wayfinding results are not transferable to all situations: Our highly schematic maps can only be constructed for non-circular street layouts, as can be seen in the schematic maps of the basement. For the common route maps which only display one route this is not a problem. For other maps, the rather strict construction constraints have to be relaxed and e.g. turns have to be allowed, too. From a navigational point of view, the floor plan might also be improved e.g. by marking corridors in a different colour, probably leading to faster encoding times and maybe also less errors. Our results might therefore depend on the kind of maps we used. The point we wanted to make, however, was how little information is sufficient for good performance. In any case, this information about where to turn at a decision point should never be omitted! More information could be helpful, but less information will probably be detrimental. This point also applies to generalising to other settings than multi-level buildings, e.g. cities. The building used was rather complex. For more simple environments, other results might be expected, but at the same time any map might be obsolete in a simple setting. The complexity of our building, however, shows the importance of unambiguous turning information for non-trivial wayfinding tasks. Unlike in a building, in a city there is only one "floor", but this floor extends much further horizontally. Both are rather complex and they both are environmental spaces according to Montello's (1993) definition, therefore the results probably can be generalised.

Our results as well as wayfinding literature regarding maps in comparison to signs (Butler et al., 1993; Hölscher et al., in press) and verbal directions (Meilinger & Knauff, submitted; Schlender, Peters & Wienhöfer, 2000) suggest: When trying to reach a goal in an unknown environment unambiguous turning information at decision points is more important than survey knowledge. May your route knowledge be communicated by signs, verbal directions or maps – this is the type knowledge you need!

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4 Discussion

The experiments described in this thesis examined various aspects of strategies that navigators use to orient in environmental spaces. In the following chapter we will summarise and evaluate these results. As a last part of this discussion we will like to propose a theoretical framework for a memory structure and strategies used by navigators to orient in environmental spaces. The predictions from this framework might lead the way for new step by step studies completing our picture of strategies for orientation in space.

4.1 Summary and discussion of the individual studies

The first three studies of this thesis focused on memory strategies that navigators use to orient in environmental spaces. The main question was, which strategies navigators use to memorise environmental spaces.

4.1.1 Study 1: Memory strategies applied for wayfinding

In Study 1 (3.1, "Working memory in wayfinding") participants learned a route through a photorealistic virtual environment directly by watching a video while performing a secondary task. During learning a participant either performed a visual, a spatial, a verbal, or no secondary task. The pattern of interference with the secondary tasks indicated that the spatial and the verbal strategy were involved in memorising the routes more strongly than the visual strategy. It seems that human navigators recruit the verbal system even though this verbal system probably evolved as a solution for other purposes than spatial orientation. Among others, this observation led to the formulation of the dual coding theory for spatial orientation (see 4.2). Study 1 not only indicated that navigators use a verbal strategy to orient in previously unknown environments (2.5.3.4). It also contributed to the differentiation between a visual and a spatial memory strategy. Experiments with figural spaces led to such a differentiation (2.5.3.2). However, for spatial orientation – one of the main purposes for a visual or spatial memory strategy as was proposed - this was not examined before.

4.1.2 Study 2: Does the spatial memory strategy rely on figural spaces?

Due to the preferred use of a spatial compared to a visual strategy, the question arises which space navigators use. Do they use the figural space of a map, as was suggested in cognitive map theories (2.4.3) or do they use the surrounding environment with the geometry of the surrounding vista space as the immediate available cue (2.3.1.2). Study 2 (3.2, "Ask for directions or use a map") and Study 3 (3.3, "From isovists via mental representations to behaviour ") focused on that question. Study 2 investigated whether navigators use figural spaces for wayfinding. To induce a figural space strategy, we gave participants a map displaying a route and asked them to walk this route. This was done for the same two routes as in Study 1, however, the participants walked through the real city and did not navigate through the virtual model. Participants of the control group got verbal directions, which induced a verbal memory strategy. Transforming spatial information that was encoded in a reference frame of a figural space into some other reference frame leads to specific costs (2.4.5). When measuring survey knowledge in the map perspective, no transformation should have occurred and indeed, participants in Study 2 that used a map to solve the task used different information than participants that only got verbal directions. However, when both groups of participants had to apply this knowledge to wayfinding, no differences between the groups could be observed. A power analysis and similar results in two other studies (2.4.6.4) indicate that the effect is reliable. We hypothesise that participants who used the map did not exclusively apply one single strategy (i.e., to encode the map directly as a figural space and rely on that representation). Similar to Study 1, participants seemed to use a verbal strategy. Applying such verbal strategy, participants were able to transform the knowledge from reference frame of the map to the reference frame in which the environmental space was encountered already during encoding, i.e., when the map was still present (2.3.2.1.1). With both groups relying mainly on a verbal strategy similar wayfinding results can be expected. Participants' subjective reports also indicated the use of a verbal strategy as all participants reported applying a verbal strategy. In addition, participants also showed better route knowledge when giving directions compared to drawing a route from both instructions. As in Study 1 results are consistent with a dual coding of spatial information (4.2). It seems that participants encode information from the map, however, they do not seem to use it much for a wayfinding task. These results speak against a strong involvement of figural space in a spatial memory strategy.

4.1.3 Study 3: Does the spatial memory strategy rely on vista spaces?

Study 2 did not suggest that navigators preferably use a spatial strategy that relies on figural spaces. However, participants did use a spatial strategy, as shown in Study 1. Study 3 explored whether the spatial memory strategy might rely more on encoding vista spaces encountered on a route (3.3, "From isovists via mental representations to behaviour"). Data from Study 1 was analysed comparing performance of all participants at different intersections. As indicated in reorientation research (2.3.1.2) and isovist analysis (2.4.6.2) the local geometry of a vista space seems to be a relevant cue for orientation. We analysed the geometry of an intersection applying a new direction-specific isovist analysis which takes the limited human field of view into account. Using the parameters from the isovist analysis we could cluster the intersections into two geometrically dissimilar groups, i.e., t-intersections and non-t-intersection. We could show that participants perform better at non-t-intersections with respect to wayfinding performance as well as to landmark and route knowledge. It therefore seems plausible that geometric layout of a vista spaces plays a role in wayfinding and that therefore, the strategy navigators use for spatial orientation relies at least to a certain amount on the geometry of vista space. The relevance of a single vista space was also supported by transformation costs we observed and which are typically found in vista spaces (2.4.5.2.2). Participants presumably encoded the vista space of an intersection within the reference frame they experienced the intersection the first time when approaching it (i.e., aligned with the walking direction). Consequently, recognising the intersections from other perspectives than that led to transformation costs due to misalignment with the encoded reference frame which could be observed in a decrease in performance. They again support a spatial memory strategy relying on vista spaces rather than on figural spaces.

The transformation costs observed also validate the direction-specific isovist analysis conducted in Study 3. In such an analysis not the whole 360° view from one vantage point is analysed, but a limited view corresponding to the view experienced before entering an intersection. This approach is also supported from results in Study 1. When looking at secondary task performance before, during and after crossing an intersection on a route which should be remembered, secondary task performance in the group with significant differences is lowest about three seconds before passing the middle of an intersection. This suggests that encoding processes take place which interfere with the secondary task exactly at the location proposed as a vantage point for the direction-specific isovist analysis. The direction-specific isovist analysis can be used as tool in future research clarifying the whole process from perceiving vista space geometry via mental representations and processes towards guiding behaviour.

Study 2 and Study 3 examined more specifically which space was involved in the spatial memory strategy. Results from the relevance of vista space geometry, from transformation costs found for vista space reference frames, but not for figural spaces reference frames indicated the involvement of vista spaces rather than figural spaces. These results led to the formulation of the network of reference frames theory which proposes in detail how a spatial memory strategy might look like, including representations and processes and their application for several tasks like reorientation, route and survey navigation (see 4.3).

So far Studies 1-3 were concerned with strategies for memorising environmental spaces and not with planning a route. However, memorising and planning strategies are not completely independent from each other. This is also indicated in Study 3. Participants showed equal or worse landmark knowledge for intersection where they had to remember to walk straight on. However, they performed better at these intersections in measures for route knowledge and wayfinding. We think this pattern of results can easily be explained assuming the participants adopted a when-in-doubt-follow-your-nose strategy. This strategy allows concentrating on memorising intersections requiring a turn. In that way the number of intersections to be memorised is strongly reduced, sparing limited memory resources. During wayfinding or tests of route knowledge participants just go straight on at such intersections which leads to the better performance measures observed. The when-in-doubt-follow-your-nose strategy is a nice example of how planning and memory strategies overlap. Accepting a small risk of getting lost this strategy can reduce the memory requirements a lot.

4.1.4 Study 4: Familiarity and the efficiency of wayfinding strategies

If Study 3 indicated the overlap between memory and planning strategies, Study 4 (3.4 "Up the down staircase") and Study 5 (3.5 "Schematic maps in wayfinding and reorientation") are more directly concerned with planning strategies. Study 4 examined the usage and effectiveness of theoretically relevant strategies as a function of familiarity. In the complex building used for the study participants could either stick to familiar routes, main corridors etc., which corresponded to a mere route strategy with limited route knowledge, they could apply a survey (least angle) strategy (see 2.4.2) or they could use a regional strategy of approaching the floor the goal was located in as soon as possible (cf. 2.4.4). For some very familiar routes, participants were also found to just activate their knowledge, as this route was well established in memory. Converging evidence from route choices and verbalisation protocols during wayfinding indicated, first, that walking a well known route or first approaching the goal region (i.e., the floor) led to better performance compared to applying a survey (least angle) strategy or sticking to known routes. Second, participants familiar with the building more often chose the more successful former two strategies whereas participants unfamiliar more often chose the latter two strategies. Again, a bridge to memory requirements can be made. Participants familiar either simply access memory or they preferably apply a strategy of regional planning the route to the goal region for which less memory capacities are necessary, as the wayfinding task is broken down to smaller pieces and the wayfinder gets lost less often while still using rather short routes. Participants unfamiliar might lack the necessary knowledge to plan a route in such way and they therefore often stick to familiar routes to avoid getting lost, but have to navigate larger distances. Contrary to that survey strategies lead to short paths, however, they require to represent survey relations between the current location and the assumed goal which has to be updated constantly. Such memory workload probably leads to the many errors and the relatively longer time when applying a survey strategy.

4.1.5 Study 5: Metric and non-metric strategies in wayfinding and reorientation

Study 4 showed better wayfinding performance for participants familiar with the building. In Study 5 (3.5 "Schematic maps in wayfinding and reorientation") first time visitors to the building had to do two wayfinding tasks also used in Study 4. They could use maps for wayfinding. However, map information could not compensate for the lack of knowledge acquired through direct comparison – participants performed worse. As with Study 2 transformation processes required could be responsible for that and indicate a verbal strategy rather than a spatial strategy based on figural spaces. However, Study 5 mainly focused on the usefulness of metric information. Participants used a normal map which represented metric properties like angles and distances correctly or they used a highly schematised map which only displayed turning information at decision points correctly (i.e., only route information). Participants had to solve wayfinding and reorientation tasks using these maps. Metric information is relevant to apply a survey strategy in wayfinding (2.4.2). Also the local geometry was found to be relevant for reorienting in vista spaces (2.3.1.2) and for wayfinding as indicated in isovist analysis (2.4.6.2 and Study 3). Study 5 wanted to see whether reorientation strategies in environmental spaces using maps also use metric properties like local geometry or whether participants rely more on the network structure of an environment. The results indicate that participants did not use metric relations successfully neither in wayfinding nor in reorientation. In wayfinding participants with the much simpler route knowledge map even performed better than participants with the additional metric information. In reorientation no differences between participants with metric or non-metric maps, not even tendencies, could be observed. This suggests that participants might have relied mainly on the network structure available in both maps than on local or global metric properties. Assuming a hypothesis testing strategy for reorientation with maps (cf. 2.3.2.2) this result can be explained. Matching the local geometry leads to much more possible hypothesis to be tested than matching based on the network structure. These results from reorientation and wayfinding indicate problems with metric orientation strategies. Metric orientation strategies like survey navigation are in principle able to lead to more precise performance. However, they seem to be more error prone as they are more demanding from a memory or a computational point of view. This can lead to worse wayfinding performance as observed in Study 1, Study 4 and Study 5. Also in all studies conducted for this thesis (except for Study 3 which did not measure any survey knowledge), measures for survey knowledge, e.g., pointing or map drawing were never found to be related to measures of wayfinding performance. This lack of a substantial correlation is an indirect indication that orientation strategies based on metric relations usually do not lead to a better performance – at least not for inexperienced navigators. One exception from this conclusion has to be made: when using a local vista space directly experienced before for wayfinding or reorientation, metric properties do seem to be used. This is very likely for the geometric layout, but also metric relations between landmarks within a vista space can be used. However, qualitative relations between landmarks seem to dominate over metric relations when both are in conflict (cf. 2.3.1.2.2). The network of reference frames theory could be a possible explanation for this very general observation regarding metric relations (see 4.3).

4.1.6 Summary

This thesis was concerned with strategies for orientation in environmental spaces. Regarding memory strategies used for wayfinding, we identified the involvement of a verbal and a spatial strategy which were more relevant than a mere visual strategy. These and other results led to the formulation of a dual coding theory for spatial orientation. The spatial memory strategy is likely to rely on vista spaces rather than on figural spaces. On a very general level, strategies applied for spatial orientation seem to rely on the principle of cost efficiency. Spatial memory strategies relying on vista spaces require less transformation costs than spatial strategies relying on figural spaces. The when-in-doubt-follow your-nose strategy requires much fewer decision points to be encoded in memory, while not risking to get lost more often compared to encoding all decision points. The efficient regional wayfinding strategy also reduces memory workload during planning and navigation while still providing rather short routes. Metric strategies such as survey navigation could enable more precise and, therefore, better performance in wayfinding and reorientation. However, their presumably higher memory and/or computation loads lead to worse performance in general and so metric strategies are chosen less often – with the exception of reorienting by directly experienced vista spaces.

We hope this work can contribute to the more and more detailed picture of how orientation in space works. As an end point for this thesis, but hopefully as a starting point for more research, we will propose a theoretic framework for orientation in environmental spaces. This framework consists, first, of the dual coding theory introduced in Section 4.2 which deals with the general memory strategies used in spatial orientation. Second, this framework consists of the network of reference frames theory described in Section 4.3 which more specifically proposes memory structures, processes, and strategies involved in a spatial encoding of directly experienced environmental spaces.

4.2 Dual coding in spatial orientation

4.2.1 Dual coding of figural, vista, and environmental spaces

Results from our experiments indicate a verbal encoding of spatial information. To explain these results and other results from the literature, we propose a dual coding approach of spatial memory. As mentioned in 2.5.2, we assume that humans are able to represent information in a descriptive and a depictive format (described otherwise in verbal and a visual or spatial format). The imagery debate (cf. 2.5.2) was mainly concerned with encoding verbally presented information in an additional visuospatial format. Our purpose is the inverse: verbally encoding information presented in a visual or spatial format. Inspired by Paivio (1971; 1986), we assume that information from figural, vista, or environmental spaces is not only encoded in a visual or a spatial format, but also in a verbal format. For example, we encode an intersection where we have to turn left in a visual or especially a spatial way, but due to dual coding we additionally re-code it into verbal directions like “turn left at the church.” If an item must be retrieved from memory, e.g., during wayfinding, it can directly activate a verbal or a spatial representation. However, the retrieval can also trigger references between the systems; the activation of a verbal memory trace can cross-activate an entity in the visual or spatial system and vice-versa. Recalling the verbal cue, “turn left at the church,” can activate our visual or spatial memory of that church and the surrounding streets. Similarly, standing at an intersection can activate the verbal description, “turn right,” which can then be used to retrace the route. Dual coding of spatial information can occur for figural, vista and environmental spaces. Several results indicate that this happens. Additional evidence from clustering in all these spaces will be discussed separately in 4.2.2.

4.2.1.1 Figural spaces

For the figural space of a map, a dual coding approach has been previously proposed (Kulhavy, Stock, Woodard & Haygood, 1993). Experimental results support this claim. Labeled information on a map is recalled more easily when it is presented in the appropriate positions, rather than in a separate list of labels (Schwartz & Kulhavy, 1981; Kulhavy, Caterino & Melchiori, 1989). Locations on a map are found faster when labels are placed in the map rather than places separately (Devlin & Bernstein, 1997). Participants learn more when map labels are placed *on* a building in a campus map, rather adjacent to the buildings (Kuo, 1996). These experiments show that verbal cues closely associated with a location on a map can increase recall performance.

4.2.1.2 Vista spaces

For vista spaces, dual coding can explain results in reorientation (cf. 2.3.1.2.1). Language has been found to support reorientation without being necessary for it. For example, verbal shadowing interfers with reorienting, but not so repeating syllables (Hermer-Vasquez, Spelke & Katnelson, 1999). In children, a boost in reorientation performance coincides with the development of verbal expressions like “left” and “right” (Hermer-Vazquez, Moffett & Munkholm, 2001; Learmonth, Nadel & Newcombe, 2002). Dual coding of spatial information can explain the contributions of language in these circumstances. However, humans and non-human animals are able to reorient without language (e.g., Sovrano, Bisazza & Vallortigara, 2002). Here they must rely on visual and spatial representations and cannot profit from the additional recall cues of verbal encoding.

4.2.1.3 Environmental spaces

For orientation in environmental spaces, dual coding is consistent with several empirical results. This includes studies that demonstrate the importance of verbal directions, dual task experiments, and wayfinding with maps and verbal directions. In these cases, dual coding is mainly about verbal directions as a form of route knowledge, rather than survey knowledge.

Verbal directions are a widespread form of representing and communicating routes in environmental spaces and they can be used efficiently for wayfinding (e.g., Denis, 1997; Denis, Pazzaglia, Cornoldi & Bertolo, 1999). Eighty percent of the expressions within verbal directions are concerned with actions and landmarks (Denis, 1997). This directly corresponds to the location and direction part of route knowledge; e.g., “turn left at the church, turn right at the yellow house, etc.” (cf. 2.3.1.4). Dual coding of a directly experienced environmental space (i.e., producing verbal directions from it,) provides a backup system when spatial memory fails. For example, when standing at an intersection we do not necessarily recall the street we took previously. But we might remember the verbal instruction, “turning left at a church,” and use this to guide our actions.

Verbal directions can be generated while navigating an environmental space. However, verbal directions - just like maps - can also be used for finding a goal in a novel environmental space. For verbal directions, this does not correspond to dual coding. However, in the case of maps, dual coding can take place. Producing verbal directions from maps and using them for wayfinding may avoid the transformation problems when using maps alone. Transformation problems include aligning the map with the environment and shifting from a birds-eye-view to a route perspective (see 2.4.5.2.4, e.g., Levine, Jankovic & Palij, 1982; Shelton & McNamara, 2004). Participants relying mainly on such self-produced verbal directions should show similar wayfinding performance compared to participants which were instructed with verbal directions directly. This pattern of result was found in the second study (3.2, "Ask for directions or use a map") and in two other studies (Pazzaglia & De Beni, 2001; Schlender, Peters, & Wienhöfer, 2000).

When learning a route through a real or virtual environmental space while simultaneously performing a secondary task, the involved memory systems can be traced more directly. Results from study one (3.1, "Working memory in wayfinding") and another study (Garden, Cornoldi & Logie, 2002) indicate that both verbal and spatial memory are. This is exactly what the dual coding theory predicts. In both experiments, participants reported having relied heavily on verbal encoding strategies.

In all mentioned experiments, dual coding was applied to a specific route. Indeed, route knowledge can be expressed in verbal format rather naturally (e.g., Denis, 1997). If global directions and distances are involved, however, expressing such survey knowledge verbally becomes more difficult. For example, it would be unusual to say, "the house you are looking for is 350 meters in the direction north-north east." Producing verbal route directions from a map can even inhibit performance in straight-line distance estimation compared to unrelated verbal activity (Fiore & Schooler 2002). Tasks which require survey orientation probably rely more on spatial representations acquired from direct experience. In addition one may recall a map encoded in a spatial format which was, e.g., indicated in the estimation of the start location in our second study (3.2, "Ask for your way or use a map"). In that sense, dual coding of wayfinding information is used for encoding route knowledge rather than survey knowledge. However, in the next section we will show how regions in an environmental space like city quarters might be represented via dual coding.

4.2.2 Dual coding compared to other theories of spatial memory

Our dual coding approach assumes additional verbal encoding of visual and spatial information. Several theories of spatial memory have been proposed that assume coding spatial information in two formats (cf. 2.4.4; e.g., Huttenlocher, Hedges & Duncan, 1991; Kosslyn et al., 1989; Creem & Proffitt, 1998). These approaches differentiate between a categorical format and a fine-grained, more perception based format. Such a fine-grained format is unbiased. It could be spatial in general (Huttenlocher et al., 1991), based on a coordinate system (Kosslyn et al., 1989) or linked to action (Creem & Proffitt, 1998; cf., Goodale & Milner, 1992). All these approaches agree more or less on the categorical format; it is the properties of the fine-grained system that differ between the theories.

Both the mentioned theories and the dual coding theory propose that individual facts are often stored twice. This can be realised in various ways. Categorical and fine-grained information can be stored as two instances within one system: fine-grained (e.g., as provided by perception) and in addition prototypically. Alternatively, the categorical information can be stored in another system capable of representing discrete variables and be linked to prototypical information within the fine-grained system. The dual coding theory proposes that this additional discrete system often is verbal memory. This will be explained in more detail.

In order to use categories, the distinctions between individual categories based on features must be established in long-term memory. Categories are discrete (e.g., green versus red) whereas a fine-grained representation can be continuous (e.g., any colour between green and red). We can use the fine-grained system to memorise a specific colour or the specific angle of an intersection. We can also, however, encode colours or angles of intersections categorically. Recalling information which was encoded categorically provides us with a typical or prototypic example from that category. For example, when imagining something red we usually do not imagine a bordeaux red or a pastel red. When imagining turning right we typically imagine turning right 90° and not 120° (e.g., Klippel, 2003). As the argumentation shows, we have categories in our long term memory and we can use these for memory purposes. Given that the mentioned two-system theories often remain rather unspecified, we must ask: how do we exactly store information categorically? Several solutions are possible. Instead of - or additionally to - storing the the precise colour or intersection we experienced, we can store the prototypical colour (e.g., the typical red or the 90° intersection). Storing prototypes is storing the categorical information within the same system as the fine-grained information. Alternatively, we can store the information about which category an experienced stimulus belongs to in another discrete system, e.g., another variable identifying a specific category. The categorical information can trigger prototypical information in the precise system. [1] Probably most of the mentioned theories would argue for the second solution. We can react based on categorical or fine-grained information or we can combine both. When not combining both types of information, different time courses for each system have been observed (e.g., Kosslyn, et al., 1989). Here, the categorical system is more likely linked to the left hemisphere and the ventral pathway whereas the fine-grained system is more likely linked to the right hemisphere and the ventral pathway (Goodale & Milner, 1992; Kosslyn, et al., 1989; Ungerleider & Mishkin, 1982). In this conception, colours or locations can be stored in two systems and the category system can trigger prototypical information in the fine-grained system.

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[1] Instead of linking the value of the discrete variable to a prototype, it could be linked to each member of a set of examples for that category. In this conception, however, it is difficult to explain why we recall prototypical information as one concrete example and do not recall multiple examples.

We would like to complement the rather unspecific description of the categorical system in the mentioned two-system theories by suggesting that storing a category in memory is often done by merely storing a verbal label for that category, e.g., storing "at the red house" or "turn right." We can guide our behaviour based merely on verbal information comparing our current environment with the stored category (e.g., walk a route based on verbal directions). When we are asked to precisely identify the colour of a house or the angle of an intersection, e.g., when drawing a map, we can also use stored verbal labels. Here the label "red" will trigger a prototypical red or the verbal label "turn right" will cause us to draw a 90° intersection. In that way categories triggered by verbal labels will lead to prototypical and therefore biased memory which may account for many biases found in spatial memory. [2] For example, it may account for biases towards orthogonal angles in spatial memory (cf. 2.4.4.1, e.g., Tversky, 1981) and for biases in the memory for locations. In memory for locations storing labels such as "up," "down," "left," "right" may trigger spatial categories in memory for locations on a computer screen and lead to a biased response (cf., Huttenlocher et al., 1991). Similary, labels like "at the castle" may trigger categories in memory in vista and environmental spaces again leading to biased responses (cf. 2.4.4.3, e.g. Fitting, Allen & Wedell, in press). Spatial regions may be formed using verbal labels, e.g., "downtown" or "California." Such categories have been shown to distort spatial judgements (cf., 2.4.4.2, e.g., Stevens & Coupe, 1978). Also, grouping effects due to political, semantic or conceptual similarities may be mediated by verbal encoding of spatial information (e.g., Carbon & Leder, 2005; Hirtle & Mascolo, 1986).

We do not assume that verbal labels are the only way to store categories. However, we provide an explicit theory about how categorical information could be remembered. Verbal encoding in that sense complements and specifies existing theories about categorical and precise encoding. Verbal encoding proposed by our dual coding theory also has a broader field of applicability. It is not restricted to biases in spatial memory, but also explains other orientation effects mentioned in the last section (e.g., effects from reorientation or wayfinding).

Additional verbal labelling of spatial information is not only useful for explaining mere memory effects; Cultural influences might also be mediated by verbal labels. Such labels might influence the category borders or the number of categories used. (cf., Majid, Bowerman, Kita, Haun & Levinson, 2004). In children, verbal labels might highlight specific distinctions in their environment which they would not necessarily have observed by merely interacting with the environment (Thomasello, 1999).

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[2] Some theories very explicitly predict how categorical information and precise memory combine, making quantitative predictions of our responses (e.g., Huttenlocher et al., 1991; Allen & Haun, 2004). The central issue is, however, that the biases are due to categorical encoding, which is often - as we assume - stored verbally.

Verbal labelling as a mediator for cultural influences also relates to embodiment and to the grounding problem of how knowledge is connected to the world from which it is acquired and how it is then used in order to act (e.g., Barsalou, Simmons, Barbey & Wilson, 2003). A visual or spatial representation acquired while navigating through the world is probably well grounded. It is closely related to the perceptual input and probably can be used by an embodied agent for retracing a route without translating it into a more abstract (e.g., propositional) format and without having to rely on complex higher-level cognitive processes. Most non-human animals are thought to navigate on this level. The dual coding theory proposes that we additionally recode this spatial format into a verbal format. This involves further abstraction from the perceptual input. However, the spatial representation might also ground the verbal representation at a higher level.

Our dual coding approach suggests that verbal labels are encoded in addition to fine-grained information. However, what information could be dual-coded? Probably dual coding can take place on all dimensions represented in our brain, which could encompass colours, forms, faces, movements, etc. For the purpose of orientation in space, mainly visual and spatial memory are relevant. As mentioned before, both visual and spatial stimuli can be encoded verbally (e.g, "red" or "turn right") or they can be encoded in the same fine-grained format in which they were experienced. In dual coding, one memory system, verbal memory, is recruited to help support another system, visual or spatial memory, despite the fact that they both might have evolved as a solution for completely different problems.

As the verbal memory system exists anyway, computationally inefficient dual coding might make sense. Dual coding would not put a strain on available resources, but would take advantage of additional capacities available anyway. A second computational argument for dual coding comes from the reliability of a storage system. For a reliable storage system, it is superfluous to store information twice, because the very same information would need more capacity. For a not-so-reliable storage system like the brain, which tends to forget things, it makes sense to store information twice. If one memory trace is lost, the information can still be derived from the other memory trace.

The dual coding theory is mainly concerned with memory. It predicts better performance sut to the use of multiple memory systems and explains biases due to categorical encoding. However, by representing spatial information verbally, this verbal representation is accessible again as an input to our reasoning (Clark, 2006). This allows for new ways to draw conclusions about our spatial environment. For example, after turning right twice in a grid city, wayfinders might conclude that they are walking back in the direction in which they were previously travelling. They could come to that conclusion also based exclusively on their spatial or fine-grained representation (e.g., mentally simulating their former path while updating their original orientation). However, with verbal representations they gain multiple options for reasoning which allow for much more flexibility as well as individual preferences in strategy choice.

In summary, dual coding in spatial orientation can explain better memory performance in map recall, the usefulness (but not the necessity) of language for reorientation, results from secondary task studies in wayfinding, and similar performance levels in wayfinding with maps and verbal directions. Dual coding complements existing two-system theories for spatial memory by providing the more precise hypothesis that categorical encoding is done verbally. It can, therefore, also account for many biases found in spatial memory. Dual coding may be a mediator for cultural influences in general, it might be a step towards solving the grounding problem, and it may provide the base for more complex reasoning. Verbally encoding a space is not only a useful memory strategy, but also enables other orientation strategies to build upon on that verbal encoding.

So far, dual coding in spatial orientation has focused on the verbal memory strategy, i.e. verbal memory and its interaction with visual or spatial memory. In the next section, we will discuss the basis of visual and spatial memory strategies in more detail.

4.3 The network of reference frames theory

In the following section we would like to describe a new theory about spatial memory as well processes and strategies operating on this memory. This theory has speculative character and will have to show it's value in future experiments.

4.3.1 Structure and processes assumed

4.3.1.1 Structure

The network of reference frames theory describes spatial memory for environmental spaces (for an overview see Table 1). It assumes that we encode multiple interconnected reference frames. Each reference frame can be described as a coordinate system with a specific orientation. These reference frames form a network or graph. A node within this network is a reference frame referring to a single vista space, so the basic unit in the network is always the reference frame of a vista space. Within this vista space reference frame, the location of objects and the surrounding geometry are specified. Objects themselves provide reference frames of figural spaces specifying the locations of features within this figural space. The edges in the network define the perspective shift necessary to move from one reference frame to the next, which usually corresponds to moving from one vista space to another. Such a perspective shift consists of both a translation and a rotation component. For example, suppose you move forward 150 meters and then turn right 90°. You are now looking into another street, experiencing a new vista space with its own reference frame. Perspective shifts all point to another reference frame, they may differ in precision and the association strength with which they connect the two reference frames. The more familiar a navigator becomes with an environmental space, the more precise a perspective shift will become and the more strongly the perspective shift will connect two reference frames.

The network of vista space reference frames connected via perspective shifts is stored in long-term memory. Several processes shape or operate on this memory. These processes are encoding, reorientation by recognition, route navigation, and survey navigation.

Structure

network (graph) consisting of nodes connected by edges

node: a reference frame with an orientation specifying locations and orientations within a vista space; within this reference frame figural spaces (objects) and especially the geometric layout are encoded

edge: perspective shift, i.e., translation and rotation necessary to move to the next reference frame; perspective shifts point to the next reference frame and differ in precision and association strength

Processes

encoding: first time experience or the geometry of a vista space can define a new reference frame; the visual scene itself, updating, or global landmarks can provide the perspective shift to the next vista space reference frame; familiarity increases the accuracy of the perspective shift and the association strength of this connection.

reorientation by recognition: recognising a vista space by the geometry or landmarks it contains provides location and orientation within this vista space and the current node/reference frame within the network

route navigation by activation spread: an activation spread mechanism provides a route from the current location to the goal (or goal region); during wayfinding, reference frames on the route are pre-activated and, therefore, recognised more easily; recently visited reference frames are deactivated

survey navigation by imagination: if one imagines connected vista spaces not visible step-by-step within the current reference frame, it is possible to retrieve direction and estimate of straight line distance to distant locations; this can be used for shortcuting, a least angle strategy, or pointing

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Table 1: Overview of the network of reference frames theory

4.3.1.2 Encoding

Visiting an environmental space for the first time. Encoding describes the process of constructing a memory trace for environmental spaces through initial and continued contact with the environmental space wether the environmental space is real, virtual, or imagined. Encoding happens rather automatically. When navigating through an environmental space for the first time, we perceive vista spaces. Such a perceived vista space corresponds to a reference frame. The orientation of that reference frame might be determined by the view from which the vista space was experienced in the first place (cf. Mallot, 1999, Wang & Spelke, 2002) or it might be determined by the salient geometry of that vista space (cf. McNamara & Valiquette, 2004). In natural situations, these two directions usually coincide. For example, when entering a street or a house, our first view of the street or house is usually aligned with the geometry of the surrounding walls.[3] Within this established reference frame, the geometry of the enclosure is encoded (e.g., walls, hedges, the edge of a forest, houses or large objects). This geometric layout is the main constraint for locomotion. It is encoded as one unit deprived of surface features like colour or texture. In addition to the geometry, locations of objects, such as landmarks, can be located within such a reference frame of a vista space.

After encoding an individual reference frame, a navigator moves on and encodes other reference frames corresponding to other vista spaces. These vista spaces must not necessarily be adjacent. These two vista space reference frames will be connected via a perspective shift (i.e., the translation and rotation, necessary to get from the first reference frame to the second). This perspective shift can be derived, (1) from the visual scene itself, (2) from updating during navigating between the two vista spaces, and (3) from global landmarks visible from both vista spaces.

Deriving the perspective shift from the visual scene is shown in the example of standing in the corridor of a house and watching the kitchen door. The kichen door provides us with the information of where (translational component) and in which orientation (rotational component) the kitchen is located with respect to the reference frame of the corridor - assuming the kitchen is behind the door and the two are aligned. Extracting the perspective shift from the visual scene itself, however, only works for adjacent vista spaces with a visible connection.

For non-adjacent vista spaces, updating can provide the perspective shift. In doing so, one’s location and orientation within the current reference frame is updated while moving away from its origin, i.e., navigators track their location and orientation relative to the latest encoded vista space. When encoding a new reference frame, the updated distance and orientation within the former reference frame provides the necessary perspective shift to get from one reference frame to

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[3] In fact, when entering a street or a house, we perceive part of the street or the room after the entrance door before our view widens and we can see the ‘whole’ vista space. However, these short first glimpses of a vista space do not seem to determine the orientation of the reference frame in which we encode this vista space. This might be due to either waiting to be aligned with the geometry of the vista space or alternatively until the change in visible geometry falls under a certain threshold. The latter case happens when we see the whole street or the whole room. After that moving around produces little or no changes in the visible space. Contrary to that the visible space changes a lot while entering the space.

other one.[4] In that sense, updating can providing the "glue" connecting locations in an environmental space (cf., Loomis, Klatzky, Golledge & Philbeck, 1999). Two important issues have to be mentioned: First, we assume that ones location and orientation can only be updated with respect to one frame of reference at a time. This will typically be the last reference frame encoded. Encoding a new reference frame always implies switching the updated reference frame. Second, although updating can provide perspective shifts over larger distances, errors still accumulate (cf. 2.3.1.3). Therefore, obtaining perspective shifts from updating, e.g., as blind people must do, will often result in rather unprecise perspective shifts – the more so the further apart two vista space reference frames are located. Updating can not only provide a navigator with a perspective shift, but can also work as a lifeline saving a navigator from getting lost. As long as navigators are able to update the last reference frame visited, they are able return to the origin of the last encoded reference frame (i.e., they are oriented).

A third possibility to get a perspective shift when already located in the second reference frame is by self localising with respect to a global landmark also visible from the first vista space reference frame, e.g., a tower or a mountain top. Self localising provides a navigator with the position and orientation with respect to the reference frame in which the global landmark was first experienced. This is the perspective shift necessary to get from the first reference frame to the second one.

Repeated visits of an environmental space. The network of reference frames theory proposes that when navigating through an environmental space for the first time, navigators encode a vista space reference frame and connect it to an existing vista space reference frame by a perspective shift. In such a way, a chain of reference frames is constructed step-by-step wich is a representation of the route navigated. When navigating through the environmental space repeatedly, new vista spaces can be encoded and connected with a known route, e.g., when turning from a known street into an unknown one. In such a way, the route is extended to a network of reference frames. Several perspective shifts point from one reference frame to several other reference frames, specifying the connections within the network. However, apart from adding new vista space reference frames not visited before, several other things can happen while repeatedly navigating an environmental space: new perspective shifts can be added between known vista space reference frames, the perspective shifts become can more accurate, the strength of associating between two reference frames can increase, and additional reference frames can be established between two existing ones.

Adding a new perspective shift between known vista space reference frames happens, e.g., when navigating between two familiar, but independently learned,

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[4] The same argumentation applies for updating the last reference frame relative to our current egocentric location and orientation. Then this perspective shift has to be inverted before being stored.

areas for the first time. A vista space reference frame from area one is then connected to a know vista space reference frame from area two. In that way, the two areas are connected. Within a known area, walking an unknown street can also provide one with a new shortcut between two vista spaces. And even walking a known route in reverse direction for the first time provides a navigator with new perspective shifts in a backward direction. Then, two vista space reference frames on a route are connected with two perspective shifts each, one providing the perspective shift to get from reference frame A to reference frame B, the other providing the perspective shift to get from reference frame B to reference frame A. In principle inverting one perspective shift would be sufficient to also get the opposite perspective shift. However, we assume that such an inversion process would be error-prone and costly and would, therefore, usually not be applied.

Not only are new perspective shifts are added to the network during repeated visits, but existing perspective shifts become more precise. This increase in precision corresponds with a shift from route knowledge to more precise survey knowledge. In the network of reference frames theory, the precision of survey knowledge directly depends on the precision of the perspective shift (for a similar model for updating see Fujita, Klatzky, Loomis & Golledge, 1993). For many people, perspective shifts will be imprecise after the first visit. In principle, this could be as simple as a vector of standard length pointing into one direction without any turning information at all which seems to be the general case with landmark navigation in ants and bees (cf. 2.3.1.4.3; e.g. Collett, Collett, Bisch & Wehner, 1998; Menzel, Geiger, Joerges, Müller & Chittka, 1995). After turing in this direction, the navigator could just head on until recognising another vista space again. This 'when-in-doubt-follow-your-nose' strategy was described in the third study (3.3; "From isovists via mental representations to behaviour"). On this level, the encoded information corresponds to route knowledge. A navigator is able to find a route without knowing the precise spatial relations between individual reference frames.

When navigating the same vista space reference frames again, the perspective shifts can become more and more precise. More and more precise perspective shifts are identical with more and more precise survey knowledge. This corresponds to the original claim that route knowledge usually develops before survey knowledge (e.g., Siegel & White, 1975). However, survey knowledge does not have to develop at all (e.g., Moeser, 1988) or can in principle also be observed after just one or two learning trials (Holding & Holding, 1989; Montello & Pick, 1993). Correspondingly, the perspective shifts may be precise enough to successfully apply a survey or least angle strategy after little experience or they do not increase much in precision even after extended experience. Here, large individual differences due to the sense of direction can be expected (cf., Hegarty & Waller, 2005; Sholl, Kenny & DellaPorta, 2006). Being able to update the global orientation while navigating an environmental space will result in more precise updating, especially regarding the angles between two reference frames. Therefore, people with a good sense of direction will also acquire more precise survey knowledge more quickly.

Multiple navigations of one specific perspective shift not only increases precision, but also increase the association strength of the perspective shift. Association strength is important, especially for route navigation, and will be explained in its respective section. As a consequence, main roads travelled more often will have more precise perspective shifts with higher association strengths compared to paths through side streets travelled less often. Recalling a perspective shift with a higher association strength will be faster. Such perspective shifts will also be more precise. The speed of recall can, therefore, indicate to a navigator how reliable a recalled perspective shift is. This also applies for recalling routes, i.e. chains of perspective shifts with reference frames in between.

Adding new reference frames between two existing ones is a final means of increasing knowledge about an environment is. This might, e.g., happen on a curvy road. Representing one reference frame at the start of the route, one at the end, and a perspective shift in between does provide some information about the road. However, to map the route in more detail, more reference frames can be added in between, each one connected by a perspective shift with the following one. Adding such new reference frames does not necessarily replace the existing perspective shift which connects the reference frames at the start and the end of the route. However, this reference frame will not increase in accuracy and association strength any more.

One important point to notice is that the network of reference frames theory only applies to environmental spaces that are experienced directly. It does not tell anything about acquiring knowledge from maps or descriptions. However, we can use instructions like maps, signs or verbal directions to find a goal and experience an environmental space during that travel (cf., study two, 3.2, “Ask for directions or use a map”). Experiencing environmental spaces directly could be done by navigating through a real or a virtual environment – with the acquired knowledge, especially precise perspective shifts, probably depending heavily on the quality of the virtual reality setup (cf. 2.4.6.5). Apart from navigating real or virtual environments, the environment might also be imagined, e.g., while reading a book or studying a map. In principle, it could be possible to encode knowledge from imagined navigating, although this will be a rather artificial case. The last section described how knowledge about an environmental space is acquired according to the network of reference frames theory. In the following sections, we will discuss how this knowledge is used to achieve certain goals such as reorientation or wayfinding.

4.3.1.3 Reorientation by recognition

When lost within a familiar environmental space, the principal mode of reorientation will be by recognising a single vista space within this environment. This can be accomplished using the geometry or salient landmarks located within that vista space (cf. 2.3.1.2 and study three "From isovists via mental representations to behaviour"). Recognising a vista space provides navigators, first, with their location and their orientation within this vista space. Second, recognising a vista spaces provides navigators with their location within the network, i.e., in which node or vista space reference frame they are located. Their exact position with respect to currently hidden locations in the environmental space, however, has to be inferred from memory. This will be explained in survey navigation by imagination.

4.3.1.4 Route navigation by activation spread

While oriented within a familiar environmental space and wanting to reach a specific location within that space, one usually needs a route to travel to this goal (cf. 2.3.1.4). We assume an activation spread mechanism to explain the selection of a route (cf. Trullier, Wiener, Berthoz & Meyer, 1997). Within the network of reference frames, activation from the current reference frame (current node) spreads along the perspective shifts (edges) connecting the various reference frames (nodes). Here, the association strength of perspective shifts is important. The association strength is higher for the most navigated perspective shifts. Activation will be spread faster along those edges higher in association strength. If the activation reaches the goal node, the route transferring the activation will be selected (i.e., a chain of reference frames connected with perspective shifts). If several possible routes are encoded within the network, the route that spreads the activation fastest will be selected for navigation. This route must not necessarily be the shortest route or the route with the least number of nodes (reference frames). As the activation propagates easier via highly associated edges, routes with such edges will be selected with higher probability. Therefore, familiar routes will be selected more often than unfamiliar routes, even if the unfamiliar routes are be shorter or consist of fewer nodes (reference frames).

During navigation, the perspective shift provides navigators with the information about where to move next, i.e., perform the perspective shift. If the perspective shift is rather unprecise, navigators will just have an indicated direction in which to move. Moving this direction, they will eventually recognise another vista space reference frame. This corresponds to the when-in-doubt-follow-your-nose strategy (cf. study three "From isovists via mental representations to behaviour"). While navigating to the next reference frame, navigators will update their location and orientation with respect to the current reference frame and, therefore, stay oriented as long as updating works. When the next vista space is recognised, it becomes the current reference frame which then is updated. For that, the old reference frame has to be deactivated (cf. Page & Norris, 1998). Preactivating the reference frame of a route will facilitate recognition. When successfully navigating a known route, the perspective shifts of that route will eventually become more precise and their association strengths will increase, making it more probable that the route will be selected again.

4.3.1.5 Survey navigation by imagination

Survey navigation in the sense used here encompasses making novel shortcuts or pointing to locations not visible within the current vista space. Updating a location and then walking back to it on a new route or navigating relative to visible landmarks (guidance) is not considered survey navigation (cf. 2.4.3.4). For example, global landmarks reduce the task of navigating the environmental space to navigating the vista space defined by the global landmarks. The network of reference frames theory explains survey navigation with imagination. A navigator imagines vista spaces not visible within the reference frame of the current vista space. The current vista space can be the one physically surrounding the navigator or another vista space that is imagined. Form the current vista space's reference frame, a perspective shift provides the direction and orientation of the connected reference frame. With this information, the navigator imagines the next vista space within the current frame of reference, e.g., the next street not visible from here is running from there to there. So the second vista space is included in the current reference frame. Now a third vista space can be included using the perspective shift connecting the second and the third vista space reference frames. In that way, every location in the surrounding environmental space can be imagined as if looking through the visibility borders of the current vista space. Now the navigator can point to distant locations, determine the straight line distance to a location, and try to find a shortcut, i.e., apply a least angle strategy. The navigator's performance will be better the more precise the individual perspective shifts are. Contrary to the rather automatic processes of encoding, reorientation by recognition, and route navigation by activation-spread, survey navigation is a deliberate strategy appied by humans. Again, an important assumption of the network of reference frames theory is that there is only one current vista space reference frame per time, either the one surrounding the navigator or a familiar reference frame they imagine. Navigators cannot be simultaneously located within two reference frames.

In summary, the network of reference frame theory proposes that global survey relations between distant locations are not stored as such in memory, but that they are constructed online from local relations using imagination (cf. Wang & Brockmole, 2003). As no global relations are stored, the encoded environment does not have to be consistent globally, i.e., short cutting is also possible when navigating impossible virtual environments (cf. Schnapp & Warren, in press).

4.3.2 The network of reference frames theory in the theoretical and empirical context

We have described the structure and the processes assumed in the network of reference frames theory. In the following, we will discuss several aspects in more detail and relate them to the results from this work and from the literature.

4.3.2.1 Vista space reference frames as the basic unit in knowledge of environmental spaces

In 2.4.3.5 we argued that our spatial knowledge cannot consist of one large, continuous, and integrated unit, e.g., a map where the locations of our bathroom, the city hall, New York and the Eiffel tower are represented within (e.g., Wang & Brockmole, 2003). Similarily, there is not one single coordinate system or reference frame underlying all spatial information. Our spatial knowledge must be partitioned into smaller units or reference frames and their relations with each other. The network of reference frames theory proposes that this basic unit is a vista space. Having smaller units as basic units, such as individual objects (e.g., cobble stones), would result in many more relations between the units which would have to be represented. Larger units, e.g., whole buildings or quarters in a city, would result in much more information represented within one unit.[5] This additional information would place a load on limited working memory resources without providing much relevant information. Several other arguments favour vista spaces as the basic unit in spatial orientation.

A vista space is the largest possible unit provided directly by visual perception. We do not perceive environmental spaces as such; we only perceive vista spaces. We can imagine or perceive a town from bird's eye view, but then we perceive a vista space, as the whole space is visible. We can also imagine vista spaces not visible from our current location. However, we then imagine the current vista space extending beyond the visibility border adding locations within the reference frame of the current vista space. When looking at a map, we do not perceive an environmental space, but rather a figural space representing an environmental space. When encoding units larger than vista spaces, several percepts would have to be integrated, something which is not done spontaneously (2.4.3.3). Encoding units smaller than vista spaces, e.g., objects, increases the number of relations to be encoded.

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[5] The idea of a basic unit for orientation implies that a unit is only activated as a whole and not parts of it.

A vista space is not only the largest spatial unit perceived directly, but it is also the unit directly relevant for locomotion, reorientation, and adding the connected perspective shifts necessary for route navigation. The geometry of a vista space especially specifies the possible areas to locomote towards. The perspective shifts connected with a vista space indicate the possible alternatives in route navigation. When lost, reorientation is usually accomplished by recognising the geometry or landmarks of a specific vista space (2.3.1.2).

For survey navigation, the network of reference frames theory assumes that vista spaces must be integrated. This is assumed to be done by imagination. Encoding units larger than vista spaces with one underlying reference frame should enable shortcutting without more difficult problems. However, humans have difficulties taking shortcuts in spaces larger than vista spaces and non-human animals (at least mammals) are rather unlikely to do so at all (2.4.3.4).

Visibility has also been found to be correlated with performance, indicating the relevance of vista spaces. The presence of more corridors on a route also leads to bigger errors in Euclidean distance estimation (Thorndyke & Hayes-Roth, 1982). Learning a real or virtual environmental space is easier with full view down a corridor than when visual access is restricted to a short distance, which results in more vista spaces that must be encoded (Gärling, Lindberg & Mäntylä, 1983; Stankievicz, Legge, Mansfield & Schlicht, 2006). An environmental space can be divided into multiple vista spaces. The number of vista spaces that can be reached by crossing, e.g., two other vista spaces, is called integration. Integration correlates with average flow of road users as well as with individual route choices (2.4.6.2).

Lastly, evidence from neuroscience for vista spaces as the basic unit in spatial memory is found in research on hippocampal place cells. Place cells as a neural basis for locations in an environment seem to encode locations within a vista space and not within an environmental space or with respect to smaller spatial units (see 2.3.1.2.4).

To sum up: arguments for vista spaces as the basic unit in spatial memory used for orientation state that smaller units result in far more relations to be considered; vista spaces are the largest unit given in perception; vista spaces are directly relevant for locomotion, reorientation and route decisions; survey navigation, which has to integrate larger areas than vista spaces, poses problems to the navigator; and finally the range of visibility is a strong predictor for performance and hippocampal place cells seem to be bound to vista spaces.

4.3.2.2 The relation between vista space reference frames: Network vs. hierarchic structure of environmental spaces

Hierachic theories of spatial memory have been very prominent (2.4.4.2; e.g., Hirtle & Jonides, 1985; Stevens & Coupe, 1978; Taylor & Tversky, 1992). In such views, smaller scale spaces are stored at progressively lower levels of the hierarchy. Contrary to these approaches, the network of reference frames theory does not assume environmental spaces to be organised hierarchically, but assumes environmental spaces are organised in a network. There is no higher hierarchical layer assumed above a vista space. All vista spaces are equally important in that sense. They are connected with each other, not with a higher order entity. This does not exclude vista spaces themselves from being organised hierarchically. We even think it is quite likely that they are organised hierarchically and will discuss this in the next section in more detail. However, on the level of environmental spaces, no hierarchic structure is assumed.

One argument for hierarchical structuring is based on clustering effects. As such effects are found in environmental spaces, they must be explained (cf., 2.4.4.2; Allen, 1981; Hirtle & Jonides, 1985; Wiener & Mallot, 2003). We propose that these effects are explained by dual coding of regions of the environmental space and not by the structure of the spatial memory itself, i.e., the structure proposed by the network of reference frames theory (4.3.1, cf. Friedman & Brown, 2000). Experiments show that distance judgements (Allen, 1981; Hirtle & Jonides, 1985) and route decisions between equal length alternatives (Wiener & Mallot, 2003) are influenced by regions within the environmental space. Dual coding theory proposes that categorical effects are due to the generation of verbal labels associated with spatial or visual memory (4.2). In that sense, all vista spaces of a region can be linked to the same verbal label. Fine-grained spatial memory, as described by the network of reference frames theory, and biased categorical memory triggered by the verbal label can both influence distance estimations and route decisions leading to the observed biases. Similar explanations for such effects can be found in the literature (cf., 2.4; e.g., Huttenlocher et al., 1991).

Dual coding can also account for regional route planning (3.4, study four "Up the down staircase"; Wiener & Mallot, 2003). In such a case a verbal label is associated with all elements of a certain region, e.g., the level of a building or a quarter of a city. The activation spread mechanisms used for route planning can select the route which first spreads activation fastest from the current location to the verbal label which is a route to one of the vista spaces of the region. After taking this route and reaching the desired region, route planning within this region can occur.

The network of reference frames theory does not assume a hierarchical structure on the level of environmental spaces. Thus it does not assume a higher-level node that groups a set of vista spaces together and provides common frame of reference for these vista spaces. Whether this assumption is supported must be shown in future experiment.

4.3.2.3 The substructure of vista spaces

The network of reference frames theory is concerned with orientation in environmental spaces. Except for the importance of geometry, the exact internal structure of vista spaces is not very important for the network of reference frames theory. However, here we would like to present some issues that will become relevant in the future discussion. We propose a hierarchic structure for the representation of vista spaces, which is in line with recent theoretical positions (e.g., Feldman, 2003; Ullman, 2006). As our concern is spatial orientation, we want to emphasise, first, that some hierarchic entities have their own reference frames and, second, we want to concentrate on three hierarchical levels which seem relevant for spatial orientation without excluding the possibility of a more hierarchic levels. On the top level, we assume a vista space reference frame which corresponds to the geometry of the vista space. Located within the vista space reference frame are figural spaces (e.g., objects) which create a mid-level with their own reference frames. Surface properties such as colour or texture are considered low-level features assigned to figural spaces or parts of the geometric layout.

As mentioned, a vista space reference frame is tightly connected to the geometry provided by the boundaries of that space (4.2.1). Its orientation might result from initial contact or from a salient orientation of the geometry, e.g., aligned with the walls of a room. The geometry can be considered as one unit and as an abstract, amodal spatial structure stripped away from surface features like colour or texture, which often change over time (see Cheng, 1986; Gallistel, 1990). In general, the geometry of a vista space stays constant. As it is directly linked with the vista space reference frame, it is updated as a whole. This is not necessary the case for objects within the vista space (e.g., Wang & Spelke, 2000). The geometry is a primary cue compared to landmarks or surface features for reorientation (2.3.1.2; e.g., Hayward, McGregor, Good, & Pearce, 2003; Hermer & Spelke, 1996; Weisend et al., 1995) and it is used for wayfinding (3.3, study three "From isovists via mental representations to behaviour"). The geometry is also immediately relevant for behaviour, as it defines the navigable space.

Figural spaces, such as objects, are located within a vista space reference frame. They are contained within a vista space and form the mid-level of the hierarchic structure of a vista spaces. Figural spaces define their own reference frame in relation to which the location of object features are defined (2.4.5.2.4). Figural spaces can be used as landmarks for spatial orientation. They can be part of the vista space geometry, as in the case of a house or a bookshelf, or they can be rather independent of that, as in the case of a dog, a street map or a chair. Figure-ground segregation can separate a figural space from the background vista space (e.g., Goldstein, 2002). Various cues are used for that, e.g., pragnanz, similarity, proximity, colinearity, good continuation, connectedness, synchrony, etc. Evidence for the hierarchical relation between figural and vista spaces also comes from a neural imaging study (Shelton & Gabrieli, 2002). In that study, participants encoded a virtual space either from a route or a survey perspective. The route perspective corresponded to the perspective in which we encounter a vista space, whereas survey perspective corresponded in that experiment more to the perspective in which we would encounter figural spaces like a map, watching an environment from birds-eye perspective. If figural spaces are contained within vista spaces, as proposed here, then brain areas concerned with figural spaces should be active in both conditions. Areas concerned with vista spaces should only be active during route presentation in addition to the areas concerned with figural spaces. Exactly this pattern of results was observed: in addition to areas active in both conditions, some areas were exclusively active during route presentation.

The lowest level in the hierarchic structure of vista spaces, is composed of surface features such as colour or texture. Survey features apply to figural spaces or to elements of the geometry such as single walls. In general, surface features as such will contribute less to spatial orientation than figural spaces and the geometry of vista spaces (3.1 study one “Working memory in wayfinding”; 2.3.1.2.3).

As a hypothesis, the three hierarchic levels might be associated with specialised functional systems in our mind which could be regarded as specific working memory systems. There are several indicators of this. Distinguishing surface features from vista and figural spaces directly corresponds to distinguishing between visual and spatial working memory (cf. 2.5.3.2). Both components can be double dissociated behaviourally and are associated with activation in different brain areas. There are also several indicators for the distinction between figural and vista spaces. Figural and vista spaces do seem to encompass different reference frames (2.4.5.2). As a consequence, using figural spaces for tasks in vista spaces is associated with performance costs due to the necessary transformation between the reference frames (2.4.5.2.4; e.g., Levine, Jankovic & Palij, 1982; Shelton & McNamara, 2004). Behavioural data showed that mental rotation, which should act on figural spaces, can be dissociated from perspective shift when the observer moves instead of the object, and which can be associated with vista spaces (Kozhevnikov & Hegarty, 2001). Performance during interaction with figural spaces does not seem to correlate very highly with performance while interacting with vista or environmental spaces (e.g., Hegarty & Waller, 2005). In neuroscience, different areas can be active in response to picture of figural spaces, e.g., a type writer, and to pictures of vista spaces (e.g., Epstein & Kanwisher, 1999). Also, the dissociation between the ventral and the dorsal stream (Ungerleider & Mishkin, 1982; Mishkin, Ungerleider, & Macko, 1983) can be related to vista and figural spaces. In that sense the “what” pathway is concerned with the identification of objects and would correspond more to figural spaces. The “where” pathway is more concerned with location in space and would correspond more to vista spaces.

From a theoretical level, one might ask which cues of a scene could in principle be used to distinguish between the three hierachical layers proposed. Spatial frequency is one such cue. Whereas high spatial frequencies correspond to surface features, middle frequencies correspond to objects and low spatial frequencies correspond to the geometry of a vista space. In addition, the distinction between concave and convex might be used. Vista spaces are mainly concave, figural spaces are mainly convex, and surfaces features are mostly flat. For the distinction between figural and vista spaces, cues used in figure-ground segregation can be transferred one-to-one.

Contrary to the non-hierarchic network structure for environmental spaces, we propose a hierarchic structure for vista spaces. On the top-level, the general geometry of the visa space is stored as a whole. Figural spaces with their own reference frames form the middle level. They are located within the vista space reference frame. The lowest level corresponds to the surface properties.

4.3.2.4 Allocentric and egocentric reference frames

In the last few years, egocentric and allocentric reference frames have been discussed intensively (e.g., Burgess, 2006; Wang & Spelke, 2002). An egocentric reference frame can be defined as a polar coordinate system with respect to the current location and orientation of the body in space (cf. 2.4.5; Klatzky, 1998). An allocentric reference frame can be defined as a coordinate system specified by a space external to a navigator. Many experiments have shown that we use both egocentric and allocentric reference frames. Objects, the geometry of a room, or a more-or-less well-learned configuration of objects, seems to be updated and recalled after disorientation as one unit. It seems, therefore, to be represented in an allocentric reference frame (2.4.5.1; e.g., Wang & Spelke, 2000; Waller & Hodgson, 2006). In the network of reference frames theory, a vista space reference frame is defined either by the initial view of the vista space or by its salient geometry. Often the first case would be considered as egocentric, and the latter case as allocentric. To avoid terminological confusion, we restrict egocentric reference frames strictly to representations in relation to the *current* location and orientation of the body, which changes constantly during navigation. Under this perspective, egocentric reference frames are transient and mainly limited to updating. On the other hand, all long-term memory is considered allocentric (for different conceptions see e.g., Wang & Spelke, 2002). As the network of reference frames theory is mainly considered with long-term memory - updating is only a possible source for perspective shifts and keeps navigators oriented when no encoded vista space is visible – this definition eliminates possible terminological confusions. No matter what defines the vista space reference frame, it is considered to be allocentric.[6] Considering all spatial long-term storage as allocentric does not, however, specify the precise conception of the allocentric reference frame. We will discuss the conception proposed by the network of reference frames theory in

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[6] The origin of the reference frame is not the navigator's body, which will move on, but a location in space the navigator happened to occupy at a certain time.

relation to reference direction theory, view-dependent theory and orientation-independent conceptions.

Reference direction theory. Reference direction theory assumes that objects are encoded with respect to one or two reference directions that function like coordinate axes, e.g., "north" (e.g., Mou, McNamara, Valiquette & Rump, 2004; McNamara & Valiquette, 2004). Retrieving information from memory works best when one is oriented along a reference direction. The memory, therefore, is orientation-dependent with respect to a reference direction. Such a reference direction originates either from the initial contact with an environment, e.g., the first view of a room after entering it, or it is changed to the main or 'intrinsic' orientation of an environment. On the level of vista spaces, reference direction theory and the network of reference frames theory do make the same predictions.[7] This is not the case on the level of environmental spaces. According to reference direction theory, one or two reference directions should underly the spatial memory for a space – here an environmental space. When oriented along one of these reference directions participants should perform better, e.g., when pointing to distant objects. Contrary to that, the network of reference frames theory predicts better performance only when one is aligned with a local vista space reference frame which can be different for each vista space. Recently, an experiment has been conducted to test these two conflicting predictions (Meilinger, Riecke & Bülthoff, in press). The results are as predicted by the network of reference frame theory, whereas no support for a global reference direction could be observed.

Even if the network of reference frames theory does not assume a common reference frame underlying environmental spaces, compass information about a global orientation like "north" should lead to better performance. Compass information could be provided, e.g., by uniform slant, distant landmarks which provide direction but no distance cues, or simply by a very good sense of direction in combination with an easy-to-update environment, such as a grid city. Several studies have shown that these factors can lead to better performance (e.g., Hegarty, Richardson, Montello, Lovelace & Subbiah, 2002; Restat, Steck, Mochnatzki & Mallot, 2004; Steck & Mallot, 2000; Sholl et al., 2006). According to the network of reference frames theory, problems in survey orientation are mainly due to problems in integrating several vista space reference frames. The mentioned factors should lead to more precise perspective shifts and, therefore, to better performance in survey tasks, but not to the establishment of a global reference frame.

View-dependent theories. View-dependent theories assume spatial knowledge to be encoded in the orientation it was experienced (e.g., Christou & Bülthoff, 1999;

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[7] The network of reference frames theory assumes an origin of a reference frame coordinate system, whereas reference direction theory does only refer to directions. However, as the orientation of a reference frame is more relevant this difference does usually not lead to different predictions.

Gillner & Mallot, 1999; Wang & Spelke, 2002). View-dependent theories, as well as the network of reference frames theory, consider environmental spaces as separated into units defined by visibility. In general, the network of reference frames theory can be seen as an extension of these theories with respect to including a third dimension, emphasising the role of geometry, and proposing a different relation between several views. Contrary to a pictorial storage of views (e.g., Gillner & Mallot, 1999) reference direction theory assumes that additional depth information is stored within a reference frame. Here geometry is especially important. Storing the geometry of a vista space (and figural spaces within) probably requires less storage capacity than storing pictorial information only. It might also allow for more flexible recognition performance, e.g., when seeing a visa space from an angle 90° to the learned orientation.[8] Also, Wang and Spelke (2002) emphasise the role of geometry for reorientation. However, contrary to them the network of reference frames theory does not consider geometric cues as input to an independent module only used for reorientation. In the network of reference frames theory geometry is integrated in the general representation of environmental spaces. It can, therefore, be used for reorientation and wayfinding (3.3, "From isovists via mental representations to behaviour"). Geometric cues can in principle be combined with non-geometric cues like colour or landmarks without having to rely on language (as was proposed by Wang and Spelke (2002)), even if geometric cues might override other cues in case of a conflict (2.3.1.2.3). In specific cases, the geometry of a vista space might determine the orientation of a reference frame even if the initial view was different. This, however, can be considered a very unnatural case, as usually geometry and initial views of a vista space coincide.

Regarding the connections between individual views, Gillner and Mallot (1999) proposed the existence of a behavioural response that is triggered when recognising a snapshot view (see also Trullier et al., 1997). The existence of such a recognition-triggered response would explain route navigation, but not survey navigation. In the network of reference frames theory, the behavioural response is replaced with the more general notion of a perspective shift. This perspective shift allows an abstraction from specific behaviour like walking or cycling (cf. 2.3.1.4.2)[9] and it allows us to represent survey knowledge in addition to route knowledge. The network of reference frames theory keeps the general graph structure of the

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[8] Encoding the geometry of vista space in a specific reference frame combines elements from view-dependency (orientation and origin of the reference frame) and from structural descriptions (geometry as one unit) which are both thought to be relevant for object recognition (Hayward, 2003).

[9] Wang and Spelke (2002) explain route navigation not by a triggered behaviour, but by approaching a landmark. While not referring to a specific behaviour, this explanation cannot account for route navigation in the sense of navigating away from a landmark which is observed e.g., in ants and bees (2.3.1.4; e.g. Collett, Collett, Bisch & Wehner, 1998; Menzel, Geiger, Joerges, Müller & Chittka, 1995).

snapshot model, but replaces the snapshots with reference frames and the recognition triggered response with a perspective shift extending the behaviour explained by the model.

Orientation-independent theories. Orientation-independent theories assume that no orientation bias is prevalent in memory as predicted by reference direction or the view dependent theories (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005; Sholl, 2001). Memory content can be accessed equally well, independently of one's orientation relative to the environment. Such performance was found in well-learned vista and environmental spaces (e.g., Sholl, 1987; Holmes & Sholl, 2005). Also, hippocampal place cells can be considered as a perspective-free neural representation (2.3.1.2.4). Experiencing a space from multiple views is likely a prerequisite for orientation-independency (2.4.1.2). Usually, orientation-independent representations are considered as additional systems to orientation-dependent ones (cf. Burgess, 2006; Sholl, 2001). This leaves open the question of how these systems relate to each other and requires a selection mechanism determining which of the systems currently guides behaviour. As the network of reference frames theory only assumes a single long-term memory structure, this problem of multiple systems does not occur.[10] The network of reference frames theory assumes orientation-dependency relative to the orientation of the vista space reference frames. Participants should perform better when aligned with a vista space reference frame.[11] In principle, rather orientation-independent behaviour could be observed when encoding multiple reference frames for one vista space. This is does not contradict the network of reference frames theory. The theory does not assume that only one reference frame is encoded for each vista space. Encoding multiple reference frames might, for example, happen when approaching a familiar intersection from a new direction. In such a case, a new, additional reference frame for that vista space could be encoded.[12] This situation is

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[10] The mechanisms operating on the memory structure either work automatically as in encoding; they directly depend on the current goal, e.g., reorienting after getting lost; or they depend on a specific strategy which has to be selected beforehand, e.g., take any available route, take a route to the goal area first, try to shortcut.

[11] Additionally, to the alignment or misalignment of a navigator with the encoded reference frame the network of reference frames theory predicts performance differences on the level of environmental spaces as a consequence of the orientation of perspective shifts. This will be discussed in the next section.

[12] Encoding one vista space multiple times requires a lot of storage capacity and is therefore inefficient. However, human memory does not seem to be limited by storage capacity, but more by how much can be encoded at a certain time and by problems of accessing the stored memory (e.g., Anderson, 1995). For encoding orientation-independent theories have to assume a lot of computation as an orientation-independent representation has to be infered from a orientation-dependent input provided by perception. According to the network of reference frames theory the information provided by perception can be encoded more or less directly. For accessing memory, orientation-independent representations have similar transformation problems like orientation-

similar to many experiments which have shown orientation-dependency with respect to the experienced views (e.g, Diwadkar & McNamara, 1997). Typically participants experience a vista space from one perspective, are disoriented, then led to a different viewpoint and experience a new view of the vista space. Orientation dependent performance with respect to the experienced views is observed. Contrary to that situation, orientation-independency is usually found after a human or a rodent moves freely around the vista space, continuously experiencing multiple views in different orientations without being disoriented (e.g., O'Keefe & Nadel, 1979; Holmes & Sholl, 2005). This might also happen when moving around blindfolded without prior disorientation (e.g., Presson & Hazelrigg, 1984; Presson, DeLange & Hazelrigg, 1989). A possible description for such situations is entering a new vista space, encoding a reference frame for it, navigating through it while being constantly and easily oriented within the reference frame by visual and proprioceptive updating. While doing so navigators are able to encode many features of that vista space, e.g., the precise geometry, multiple landmarks within the active reference frame. Such rich and well-integrated cues might attenuate orientation-dependency which is not noticed anymore. The network of reference frames theory does not assume orientation-independent representations. However, encoding multiple reference frames for one vista space or encoding well integrated cues within one vista space might attenuate orientation-dependency until it is not noticed anymore.

4.3.2.5 Asymmetry in spatial memory

The network of reference frames theory proposes orientation specificity originating from the orientation of the encoded reference frames. However, performance differences do not only originate from misalignment with stored reference frames, but also from the directionality of perspective shifts. Perspective shifts are always pointing from one vista space to another and are, according to the network of reference frames theory, not inverted easily. Tasks requiring access to the perspective shift in its encoded direction should be easier and more precise than tasks requiring access to the opposite direction, at least as long as there is no additional perspective shift encoded in the opposite direction. This assumption leads to an asymmetry in various spatial tasks which will be discussed in more detail: the route direction effect in spatial priming, worse wayfinding performance for walking a route in reverse order, and different route choices for wayfinding there and back.

After learning a route presented on a computer screen in one direction only, recognising pictures of landmarks is faster when primed with a picture of an

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dependent ones as all proposed representations have to bring memory together with the perspective from which navigators currently experience an environment.

object encountered before the landmark than when primed with an object encountered after the landmark (Herrmann, Buhl & Schweizer, 1995; Janzen, 2006; Schweizer, 1997; Schweizer, Herrmann, Janzen & Katz, 1998). According to the network of reference frames theory the directionality of perspective shifts speeds up activation spread in the direction the route was learned. Therefore, priming is faster in the direction a route was learned, as is observed in the route direction effect.

Walking a route in only one direction and then tracing it in opposite direction, usually leads to larger errors compared to tracing the route in the orientation it was learned. Being instructed to look backwards while learning the route leads to better backtracing performance than to retracing parts of the route without looking backwards or to not specific strategy (Cornell, Heth & Rowat, 1992). According to the network of reference frames theory, looking backwards enables a navigator to encode an additional perspective shift pointing backwards. This should lead to better performance compared to inverting the perspective shift encoded when navigating the route in only one direction. However, better recognition performance after turing around might also explain the effect.

Asymmetries are also found in path choices. In a familiar environment, navigators often choose different routes on the way out and back (Golledge, 1995; Stern & Leiser, 1988). According to the network of reference frames theory, different perspective shifts usually connect vista spaces on a route out and back. Due to different connections, different routes can be selected when planning a route out compared to planning the route back. For example, perspective shifts can be derived from the visible scene. As the area visible usually changes when travelling the same route there and back, perspective shifts connecting different vista spaces can be established. For example, a t-intersection becomes a branch off on the way back, providing the view to more alternative routes for which the perspective shifts can be constructed. Such situations might easily result in different perspective shifts and therefore also in different path choices.

The three effects mentioned can be explained with the directionality of perspective shifts. However, route navigation by recognition-triggered responses (e.g., Mallot, 1999; Trullier et al., 1997) can also easily be extended in order to explain such behaviours. Recognition-triggered responses or more general route knowledge are directed. Contrary to that, survey knowledge usually is not assumed to be directed (cf., Golledge, 1999; Herrmann, Schweizer, Janzen & Katz, 1998; Montello, Waller, Hegarty & Richardson, 2004; Siegel & White, 1975). Contrary to that, the network of reference frames theory predicts that also survey knowledge is directed. For a route navigated mainly in one direction, better survey knowledge performance, e.g., faster and more precise pointing and shortcutting, is predicted compared to doing so in the opposite direction. Further experiments are required to judge whether this is in fact the case.

4.3.2.6 Imagining distant locations as a difference between human and non-human navigators

The network of reference frames theory proposes that reference frames are connected via perspective shifts. This memory structure can in principle be used to explain not only human navigation, but also non-human navigation– at least in the case of mammals. Similarly, also three of the processes assumed can easily be applied to the animal literature, namely reorientation by recognition, route navigation by activation spread, and encoding. Updating is here considered a subprocesses of encoding. Updating keeps the navigator oriented with respect to the current vista space reference frame. It provides the navigator with a perspective shift together, or instead of deriving the perspective shift from the visual input of the scene or from global landmarks. These processes are very likely to have been inherited by our ancestors and might be shared with our "closer" relatives, e.g., apes and other mammals, or maybe even with "further" relatives like reptiles or birds. Common representations and processes enable continuity in phylogenetic development assumed in this work. However, apart from such commonalities we also assume differences between human and non-human navigators. Imagining distant vista spaces within the current vista space reference frame (the physical surrounding or an imagined one) is assumed as the key process to explain survey navigation. When imagining a distant location, the direction and distance to it can be estimated and used, e.g., for pointing or shortcutting. We assume that using imagination in such a way for orientation is a specific human capacity as survey navigation was not observed in non-human animals, at least not in mammals (2.4.3.4; e.g., Bennet, 1996; Wehner, 1999). We will not speculate about whether non-human animals are able to imagine at all, we only assume they do not do so for survey navigation. The imagination process is a more concrete assumption than proposing language processes as a means to overcome independent navigation processes (Wang & Spelke, 2002).

When imagining distant locations within the current reference frame, working memory has to be used. As working memory capacity is limited, the process of imagining can be limited to imagining only two additional vista spaces at a time. For example, a vista space A next to the current vista space is imagined within the current vista space reference frame. Using the perspective shift, the second next vista space B is added. After doing so, the first vista space A can be erased from working memory sparing limited working memory capacities. Alternative conceptions of survey knowledge which rely on an integrated representation, e.g. a "cognitive map", require much higher working memory load. In such conceptions, all locations between the current location and the goal location have to be represented in working memory, resulting in a much higher memory load (cf. 2.4.3).

A navigator capable of survey navigation can apply a survey (least angle) strategy to reach a goal in wayfinding. The navigator alternatively can use route navigation with activation spread to select a route directly to the goal, or the navigator can use the activation spread mechanism to select a route to the goal region first (cf. 3.4; study four "Up the down staircase"). These multiple options require a selection process. So deliberately choosing between several strategies is likely to be specific for humans. Contrary to that, non-human animals are limited to route navigation by activation spread for wayfinding and, therefore, only have to select a route and not select between different strategies to approach a goal. In the concluding remarks (4.4) we will point out other possible differences between human and non-human navigators.

4.3.3 Summary and open questions

The network of reference frames theory proposes that navigators represent directly experienced environmental spaces in a network of reference frames. A node in such a network corresponds to a reference frame specifying locations and orientations within a vista space. The geometry of a vista space in particular is encoded as a whole. However, figural spaces like landmarks and surface properties are encoded on hierarchical sublevels within the reference frame. The orientation of the reference frame originates from initial contact with the vista space or from its geometry. The edges in the network correspond to perspective shifts specifying the translation and rotation necessary to transfer from one reference frame to the next reference frame. Perspective shifts are oriented in one direction. They can be obtained from updating, directly from the visual scene, or from global landmarks. Perspective shifts differ in association strength. Repeated navigation adds new reference frames and new perspective shifts to the network. Existing perspective shifts become more precise and increase in association strength. By recognising a vista space within the network, a navigator becomes oriented in location and orientation with respect to the reference frame. Via the perspective shifts connecting the current reference frame to the rest of the network, the navigator also becomes oriented with respect to rest of the environmental space. An activations spread mechanism selects a route for route navigation. Here activation spreads from the current location to the goal or a goal region. The higher the association strength of a perspective shift the faster activation spreads. The route spreading activation fastest is selected for navigation. Familiar routes containing perspective shifts with a higher association strength will more likely to be selected by such a mechanism. When using this route for navigation, the vista spaces reference frames of the route are preactivated and are, therefore, easier to recognise. Visited vista space reference frames are deactivated. Survey navigation is explained by imagining vista spaces not visible within the current reference frame. They are mentally added behind the borders of visibility one after the other. Thus, the units of spatial memory are integrated within one reference frame only when needed. From the imagined distant vista spaces, directions and distances can be estimated and used for pointing or shortcutting.

The network of reference frames theory proposes an integrated approach, not encapsulated independent processes. The assumed representation structure can be used for route navigation as well as for survey navigation; it is the same for wayfinding and reorientation. Updating is considered a sub-process of encoding.

It can be used to obtain the perspective shift between two reference frames. In addition, updating keeps a navigator oriented with respect to the current active vista spaces reference frame while navigating further on. The quality of the perspective shifts reflects differences in experience, individual differences in the sense of direction, and differences according to the environment. For example better perspective shifts can be expected in environments with constant slant, global landmarks or a grid structure. The network of reference frames theory assumes vista space reference frames as the basic unit an environmental space is divided into. This unit is directly given in perception and is directly relevant for locomotion and reorientation. Together with the connected perspective shifts, it is directly relevant for route navigation. Smaller spatial scales are organised in subhierarchies within a vista space reference frame. No hierarchical structure is assumed above the level of vista space reference frames, but it is rather considered to be organised in a network. Dual coding of elements of our environment verbally offers an interface between the spatial and the verbal system. Additional verbal encoding of vista spaces explains clustering effects above the level of vista spaces. Verbal encoding, which also enables a regional planning strategy, is assumed to be specific for humans, as is survey navigation by imagination. Humans can deliberately choose between wayfinding strategies. In contrast, non-human animals are thought to depend on the rather automatic route navigation by activation spread. Human strategies in spatial orientation are thought to build upon and extend the rather automatic processes. The network of reference frames theory describes how spatial memory is constructed while navigating an environment and how this memory is used for subsequent spatial orientation. The theory does not make any claims about how human navigators orient with wayfinding aids such as verbal directions, maps, signs, etc.

Several open questions arise from the network of reference frames theory: (1) Which vista space reference frames are encoded from an input of constantly changing vista spaces surrounding the navigator? Salient locations, the relevance of a location for wayfinding, relative stability in the visible area during movement, or alignment with the geometry seem to be good candidates to test. (2) Where does the metric in the system come from? The network of vista spaces reference frames theory proposes visible depth cues and updating as likely sources. How these cues are integrated exactly or whether they override each other must be the subject of future research. (3) Contrary to other theories, the network of reference frames theory does not assume hierarchical nodes (or reference frames) above the level of vista spaces. Some work points into this direction, however, further experiments have to be done. (4) Results indicating relative orientation-independent performance can be explained by the network of reference frames theory by storing multiple reference frames for one vista space or by encoding a well-integrated geometric structure of a specific vista space. The exact processes must be examined in the future. (5) The network of reference frames theory proposes an asymmetry due to the orientation of a perspective shift. This explains asymmetries found in priming and route choice and predicts asymmetries in survey knowledge – another subject of future experiments.

The network of reference frames theory is meant to be a tool for research. It should serve the acquisition of knowledge through science in two ways. First, it integrates theoretical positions and empirical results, which had previously remained independent. Second, it provides ideas for further experiments and makes in some cases new predictions which can be empirically tested, i.e., no global reference frame for environmental spaces, imagination as a way to derive survey relations, and asymmetries in survey knowledge. Future research must show whether these claims are justified.

4.4 Strategies of orientation in environmental spaces - concluding remarks

Within this thesis we examined strategies of orientation in environmental spaces. Human orientation strategies build on mechanisms also found in non-human animals, for example, reorientation, updating, and route navigation. Supposably unlike to non-human animals, humans often have multiple options to reach one specific orientation goal and have to select one of them. We distinguished between memory strategies concerned with how to encode spatial knowledge and planning strategies concerned with how to approach a goal especially in wayfinding. Regarding memory strategies, Study 1 showed that navigators use a spatial and a verbal strategy rather than a visual strategy for encoding knowledge about a route. Study 2 also indicated that map users use a verbal encoding strategy. These results led to the formulation of the dual coding theory for spatial orientation which assumes that human navigators encode spaces used for orientation, not only in a visual or spatial format as probably also non-human animals do, but that humans additionally encode spatial information in a verbal format. This theory can explain biases in spatial memory, can help interpret results from wayfinding and reorientation and it can provide a basis for more elaborate strategies. Study 2 and Study 3 indicated that the spatial strategy for encoding environmental spaces is more concerned with encoding vista spaces rather than with encoding figural spaces. This is efficient regarding the higher transformation costs of figural space compared to vista spaces when applying them for orientation in environmental spaces. In addition, Study 3 showed that participants do not seem to encode all relevant decision points, such as intersections, but focus on decision points which require a turn. In order to avoid getting lost they apply a"when-in-doubt-follow-your-nose" strategy, i.e., walk straight on at intersection not recalled. Therefore, participants save memory capacity compared to encoding all intersections without a much higher risk of getting lost. Other strategies more directly concerned with planning also seem to maintain a cost efficiency criteria. Study 4 showed that a regional planning strategy leads to better wayfinding performance and is chosen more often by navigators familiar with an environment compared to a survey (least angle) strategy and/or a normal route planning strategy. The regional planning strategy can reduce memory workload during planning and navigation while still providing rather short routes. Metric strategies like survey navigation or reorienting on metric properties provided by a map can enable more precise and therefore better performance. However their presumably higher memory and/or computational loads can lead to worse orientation performance in environmental spaces compared to simpler strategies such as route navigation shown in Study 5. In particular, unfamiliar navigators do not seem to profit from metric knowledge as was indicated in Studies 1, 2, 4 and 5. The network of reference frames theory proposes an explanation for problems in applying metric relations in environmental spaces. It proposes a common memory structure for wayfinding and reorienting in environmental spaces that were directly experienced rather than learned from other sources such as maps. It gives a common framework for route and survey navigation and shows commonalities and differences between human and non-human navigators. It can explain results from various areas of spatial orientation, such as, orientation specificity, changes due to familiarity, asymmetries in spatial memory, etc. It has speculative character, however, it provides ideas as well as testable predictions for future research.

In the introduction we pointed out some assumptions underlying this work. We will now return to those assumptions here. We assumed a rather continuous phylogenetic and ontogenetic development. Therefore, various results from the literature on spatial orientation in children and in non-human animals could be integrated as was done in the theory section. However, development also means that something changes. In the following we want to summarise where we propose a change in the human orientation compared to non-human orientation and how new abilities like strategies build on top of existing abilities.

One dramatic change comes with strategic choice. We suggest that the question of which orientation mechanism is used by non-human animals is rather determined by the goal they are currently pursuing, such as walking to a location, reorienting, searching for food etc. (2.3.1.5). Contrary to that we assume that human navigators have some freedom of choice regarding the strategies they apply for reaching a goal. In wayfinding they might, for example, use a survey strategy, or compute the fewest number of turns, or use a regional route planning strategy in order to reach their goal. Most of these strategies rely on representations and/or processes already existent in non-human animals. For example, the regional route planning strategy can use the inherited route planning process with the only extention being that the activation spread mechanism does not select the route spreading activation fastest to the goal, but selects the route spreading activation fastest to the label common for all locations within a region. A fewest number of turns strategy can be seen as a new mechanism operating on a memory structure which existed before. In the network of reference frames theory we propose that a survey strategy also builds on a spatial memory structure assumed common for human and non-human navigators as well as common for reorientation and route navigation (4.3). The additional mechanisms assumed necessary for survey navigation include imagining distant locations within the current vista space reference frame. As with the other examples, some change together with existing structures enables new orientation strategies.

Another change in the development between non-human and human animals is the usage of representations which probably did not evolve as a solution to an orientation problem. Here the non-environmental space representation symbolises locations and spatial relations in the representation of an environmental space (i.e., the representation proposed in the network of reference frames theory). In that sense the "new" representations also have to build a connection to existing spatial representations. This encompases language as expressed in the dual coding theory (4.2), but also figural spaces like maps. These representations can be both external and internal. Using them for orientation involves transformation processes. As we have seen, figural spaces like maps might not be involved so much in a spatial memory strategy. As external representation, maps are, however, surely useful for planning a route and for communicating spatial knowledge, especially survey knowledge. As shown in the first two studies, verbal encoding seems to be a good memory strategy. Dual coding a space spatially and verbally might contribute to grounding the verbal representation in a visual or spatial representation closer to perception and action. Representing a space additionally in a verbal format, however, can also open new ways of reasoning about spaces based on the verbal representation. Using symbolic relations we think humans are not restricted to encoding environmental spaces in a specific format, but can use additional formats which help memorising a space and also enable new strategies based on these other formats to solve spatial problems. In order to apply such new solutions, navigators will depend on the symbolic link to translate the new solutions back into formats which can be (more) directly used for action and of which we probably share with our ancestors.

For another change in the development between non-human and human animals, we proposed planning using "as-if" actions. Although humans are surely able to plan in that way we conclude that less strong assumptions might be sufficient to explain most human orientation strategies, i.e., humans might use heuristic planning rather than complete planning. For the case of route navigation and regional planning, an activation-spread mechanism is sufficient to explain orientation behaviour. For survey navigation we proposed imagination as sufficient to explain human pointing and shortcut performance. These strategies do not include searching a space of possible states accessible by as-if actions. For many cases the assumption of a very general planning algorithm seems superfluous and specific strategies extending exising memory structures seem more appropriate to explain behaviour. This directly relates to another assumption of this work.

Specifically, we assumed specialised representations as well as processes and strategies operating on them. Along with the literature this work strongly suggests multiple processes and strategies. In the literature at times the independence between such mechanisms has been emphasised, even to the point of assuming encapsulated modules (e.g., Wang & Spelke, 2002). While still differentiating between processes and strategies such as updating, route navigation, regional route planning, or survey navigation, we also tried to show how these mechanisms relate to each other and how they contribute to and rely on a common memory structure as was proposed in the network of reference frames theory. With regards to memory strategies relying on specific representations, a differentiation between visual, spatial and verbal strategies was demonstrated by this work. Apart from verbal and non-verbal memory, this work proposed a finer distinction between strategies corresponding to different spatial scales, namely figural, vista and environmental spaces. The results of the current thesis, in addition to past results have shown that this distinction of spatial scales is a very important one. This distinction adds a great deal to characterise specific elements of spatial representations contributing to a better understanding of spatial orientation as well as spatial cognition in general.

Understanding spatial orientation and in particular, understanding human strategies underlying orientation, is a field of research which has gained growing interest over the past several years. This current work provided an overview of this field and contributed to answering some of the many open questions such as which strategies human navigators use to encode a route, or which strategies they use to reach a goal as a function of familiarity or the availability of metric information. These results led to the formulation of a theoretical framework for orientation in environmental spaces, namely the dual coding theory for spatial orientation and the network of reference frames theory. This theoretical framework incorporated results and arguments from psychology, biology, computer science, cognitive science, and neuroscience and provides new, testable predictions. It is meant to be a step forwards to approach what could be the goal of such an interdisciplinary project: that is, to provide a functional theory of orientation in space.

4.5 References

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