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# ROTATIONAL LOCOMOTION IN LARGE-SCALE ENVIRONMENTS

## A Survey and Implications For Evidence Based Design Practice

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Navigation performance in urban and large-scale built-up spaces (e.g. airports, train stations, hospitals) depends on gradual environmental perception during locomotion, and spatial knowledge acquisition, update / integration at different times along a path. Rotational locomotion is regularly involved in everyday navigation; this, combined with the fact that people cannot perceive the whole of a large-scale setting at once frequently leads to cognitive loading and disorientation incidents.

This research explores the mechanisms involved in rotational locomotion for human navigators, and the role of familiarity as well as the cost of cognitive load on orientation accuracy and spatial memory. We examine the impact of structural and featural cues on spatial knowledge update in relation to ego-rotations from the viewpoint of behaviour-based design practice and evidence-based design interventions. Based on a case study in a train station, experimenting on rotational problems in navigation, we present preliminary results emphasizing the role of environmental cues in rotational location, outline possibilities for further study, and discuss implications for evidence-based design practice and cognitive design assistance technology development.

People create structures to satisfy their needs and they modify the natural environment by regulating its characteristics. We spend a substantial part of our lives in human-designed, regulated environments with paths, tracks, streets, hallways etc serving as main arteries of human locomotion. Architecture embodies the human effort to structure space in meaningful and useful ways [Werner and Long, 2003, Bhatt and Schultz, 2017], and satisfies different representational, functional, aesthetic, and emotional needs. Navigation is essential to any environment that demands movement across large-scale spaces, such as urban, natural as well as built-up structures, even though it rarely forms the primary task [Darken and Peterson, 2002].

### NAVIGATING LARGE-SCALE ENVIRONMENTS

Finding ones way in a large-scale environment, reaching a destination, remembering the location of relevant objects, or returning to a previously visited location are some of the tasks that are combined in our everyday activities. Human navigation relies on various elements and procedures related to human sensory and cognitive abilities. Particularly, humans perceive space through different sensory channels and consequently, the wayfinding behaviour is based on "*a consistent use and organization of definite sensory cues from the external environment*" [Lynch, 1960]. Moreover, the process of navigation involves making intuitive quick decisions, applying common sense geographic knowledge [Kuipers, 1978] and qualitative methods of spatial representation and reasoning [Frank, 1992, 1996, Freksa, 1992, Bhatt and Freksa, 2010, 2015].

Human navigators are well equipped with an array of flexible navigational strategies, which usually enable them to master their spatial environment [Allen, 1999]. Most spatial or navigational strategies are so common that they do not occur to the user whilst action performance. For instance, walking in an urban space, the user hardly realises that the optical and acoustical flows give reach information about where one is headed, or if one will collide with other objects [Gibson, 1979]. However, there are incidents that indicate the limitations of human navigation abilities, as for example failure in integrating new spatial information, loose of control of the path one follows, or disorientation and confusion events even if the user has been to the place before.

### THE CASE OF ROTATIONAL LOCOMOTION

Certain environmental morphologies force a navigating user to rotate by a 180° (Fig. 1); this typically happens after a series of turn actions along a long navigation route. Consider the last time you negotiated your way back after a path with multiples turns and decision points, or the time you ended up in a decision point without remembering if you came from the right or the left path, or when you experienced surprise by expecting a familiar landmark to appear on the right instead of the left side? In many cases like these, the environment leads users to multiple turns and they end up performing ego-rotations without realising it. When this happens in a large-scale built-up environment, such as a hospital or a train station (Fig. 1), it leads to a great number of confused individuals. People are loosing control of directions and orientation, because when rotation is involved the task gets more demanding as it requires high-level cognitive awareness and attention [Waller et al., 2002].

**KEY CONTRIBUTIONS.** In the backdrop of our articulation of the "rotation problem" occurring form rotational locomotion during navigation in large-scale built-up environments, the key goals of this chapter are:

- To contextualise rotational location from the viewpoint of the broad-based research on spatial cognition, in particular, concerning mental rotation and mental representations; we survey the state of understanding of the rotational locomotion problem, including the relevant cognitive mechanisms and the related factors (e.g., environmental scale, familiarity, environmental cues);
- We examine potential ways of experimentation in embodied / real-world settings (and possibly also virtual environments); this is based on an actual pilot experiment involving navigating from one train station to another, and returning to the source location (and in between actually taking a short train trip as part of the exercise); We propose a multimodal human behaviour study methodology involving eye-tracking, user behaviour analysis, qualitative surveying etc.
- Based on the outcomes of a preliminary pilot study and its relationship to the state of the art, here we emphasise aspects of *familiarity* and *environmental cues* that seem to have a particular relationship to the rotation problem.

Based on the state of the art and ongoing experiments involving rotational location, we also present some possibilities from the viewpoint of evidence based design technology and design practice. We particu-

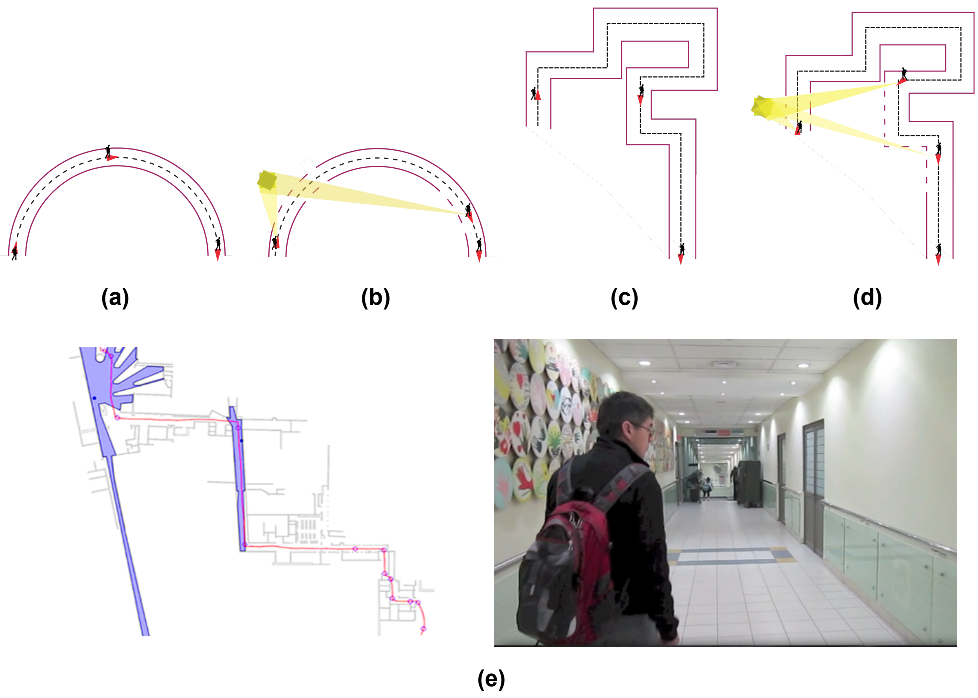



**Figure 1.** An abstract representation (a) and a sample layout of built-up space morphology (b) that forces a navigator to rotate by 180° during navigation without (a, c) and with (b, d) the support of an external landmark; (e) is a real-world example (from Hospital del Trabajado, Santiago in Chile) of a route where rotational locomotion happens in the absence of an external landmark in a manner similar to the representation in (c).

larly emphasise the translation of empirically established human-environment behaviour precedents into formal models within evidence based design practices and human-centred cognitive design assistance technologies.

**ORGANIZATION.**

With respect to the proposed contributions and goals, the chapter is organised is follows:

- Section 1 presents the definition of the problem of rotational locomotion, the involved cognitive mechanisms, and the implication in navigation;
- Section 2 includes an overview of the factors influencing the visuo-locomotive experience during navigation; in focus as factors such as the environmental scale, familiarity, and specific environmental aspects (e.g., structure, geometry, manifest cues);
- Section 3 presents an empirical case study and preliminary results as a pilot and example of multimodal experimentation pertaining to rotational location in the specific context of train stations (in Germany); the particular context is chosen for its (real-world) morphological typicality fitting the purpose of rotational locomotion; and
- Section 4 includes a brief discussion and presents next steps.

# 1 THE EFFECT OF ROTATIONAL LOCOMOTION IN NAVIGATION

Navigation is the aggregate task of wayfinding and motion. It inherently must have both the cognitive element (wayfinding), and the motoric element (motion) [Darken and Peterson, 2002, Montello, 2005]. The wayfinding process includes determination of the current location (positioning), the best path to the destination (route guidance); monitoring of the difference between current position and the calculated path (tracking), and enforcement of appropriate actions to minimize this difference [Nagel et al., 2010]. Locomotion refers to the motoric element of navigation, such as active transport or manoeuvring, that involves adjusting the orientation of perspective, as in rotating the body, or sidestepping and it is related to proprioception.

Current literature recognizes that physical and imagined translation worsen the spatial orientation of navigators and rotation has an even more prominent effect [Kelly et al., 2008, Presson and Montello, 1994, Rieser, 1989]. When a navigator needs to use a different perspective with respect to that from which he learned the environment, he is forced to align with the new imagined perspective and therefore to rotate the initial spatial frame of reference (SFR). This process implies a reduction of pointing task's accuracy and an increase in time required to align the two SFRs. Translational motions, in contrast, do not involve this cognitive effort [Huttenlocher and Presson, 1973, Péruch and Lapin, 1993]. These findings are coming from experimentations in indoor environments, but they seem to evoke a peculiar extension to outdoor environments. Rotation itself is easier to be met and more relevant to open urban landscapes than to confined built-up spaces, where paths can be rather multidirectional and often unconstrained by narrow corridors [Borri and Camarda, 2009]. Curved or turning streets, crossroads, roundabouts, urban stairways, multidirectional walking as well as transition from indoor to outdoor public spaces, involve repeated updating of spatial knowledge.

## SPATIAL KNOWLEDGE ACQUISITION AND UPDATE

The goal-driven reasoning chain that leads to actions in navigation, begins with incomplete and imprecise knowledge derived from imperfect observations of space [Norman, 1988]. Human users do not need a holistic perception of space before they are able to perform navigation. However, they are influenced by the dominant perceptual input of vision for sighted people, as well as proprioception and audition. The development of their spatial knowledge begins immediately on the first exposure of the person to an environment, with knowledge of locations, directions, and distances becoming increasingly accurate over time.

In active navigation the user is on direct environmental exposure and he extracts information for the current or other subsequent navigation tasks. Once spatial knowledge is acquired, it must be organised in such a way that it can be used during the navigation task. It is well documented that spatial knowledge that is needed for this process consists of landmarks, route, and survey knowledge [Siegel and White, 1975]. During navigation, the user continuously builds and updates his or her "*cognitive map*" [Tolman, 1948], i.e. a mental representation of the environment, storing spatial information and knowledge of relative locations and attributes of spatial features [Kuipers, 1982, Lynch, 1960], while new information about the environment is acquired [Gaisbauer and Frank, 2008]. Cognitive maps refer mental representations of an environment but they are not purely based on imagery but rather contain a symbolic quality.

Navigation in built environments typically includes changes on the heading and the location relative to the surrounding, or in other words *rotation* and *translation*. During such changes, people need to update their perspective, integrate new spatial knowledge, and maintain their orientation towards the goal. The ability to keep track of the changing spatial relations between objects and places as someone moves is known as *spatial knowledge updating* [Pick and Rieser, 1982]. Rotation-related changes seem more difficult for spatial knowledge updating than translation-related changes [Easton and Sholl, 1995, Presson and Montello, 1994, Rieser, 1989, Kelly et al., 2008]; mostly because humans' orientation abilities are negatively affected by ego-rotations and proprioceptive changes during active locomotion [Kelly et al., 2008, Presson and Montello, 1994]. However, self-movement facilitates automatic updating of spatial relations [Farrell and Robertson, 1998, Rieser et al., 1994]. Further failures in spatial knowledge update are related to cognitive processes - involving reasoning, memory, and attention, and it encompasses components of "*reference frames*" or "*perception-action couplings*" [Golledge, 1999].

### IMPLICATIONS OF ROTATIONAL LOCOMOTION ON SPATIAL MEMORY AND SPATIAL REPRESENTATIONS

In the processes of acquisition, encoding and decoding, as well as information storage, spatial knowledge and cognitive maps undergo a series of distortions that make these mental representations inaccurate or not fully corresponding to reality. As Montello [1991] describes, people's spatial knowledge is systematically distorted by the use of *heuristics* [Tversky and Kahneman, 1981] to simplify alignment and rotation information. Errors in updating an imagined heading appear tied to perceptual representations of the body [Avraamides et al., 2004], although the error is reduced when body-based information is available [Waller et al., 2004]. Errors in representation are characterized by fragmentations, distortions, sometimes overlapping of elements in different scales, simplifications, addition or omission of details in order to select the information deemed fundamental and to lighten the cognitive load that otherwise people would not be able to endure [Thorndyke and Hayes-Roth, 1981, Hochmair and Frank, 2000, Peters, 2012]. As the process of spatial rotation is highly cognitively demanding (it requires rotating a spatial frame of reference and imagining new possible perspectives and interactions with the world), research on spatial memory suggest that the rotational locomotion leads to important implications in terms of retrieval times and of accuracy of spatial knowledge, and so it substantially impairs wayfinding performance [Werner and Jaeger, 2002].

People encode spatial information, with the need to incorporate experience based on multiple views acquired during navigation and to integrate information to fully represent the whole environment [Allen, 1999, Gillner and Mallot, 1998, Werner et al., 2000]. While the idea of orientation-free representations contracted by snapshots of space coming from navigation process may make intuitive sense for this task, empirical evidence suggest that orientation-free performance is only possible under a certain set of conditions [Sholl and Nolin, 1997]. The conditions outlined include a horizontal viewing angle during encoding, a room-sized test space, and "on-path" testing. Some of these conditions suggest that spatial perspective plays a role in spatial representation use, particularly when considering how such representations are used "out of sequence". In a general view though, people encode information on an adopted spatial frame of reference based on egocentric experience to the intrinsic environment, typically from the initial experience [Werner and Schmidt, 1999, Montello, 1991], or a preference frame in accordance with some alignment or an axial relation to the geometry of the structure [Sadalla and Montello, 1989]. It has been proven that the retrieval of spatial knowledge from memory is easier when observer judges spatial relation from a heading parallel to their original perspective than from other headings [Presson and Hazelrigg, 1984]. In the case of of rotational locomotion when superposition of different SFRs is required [Huttenlocher and Presson, 1973, Péruch and Lapin, 1993], the dependency of the memory retrieval on a particular heading is documented as *alignment effect* [Shelton and McNamara, 1997].

### NAVIGATION STRATEGIES AND SPATIAL KNOWLEDGE UPDATE

People use a range of strategies in everyday navigation and wayfinding; which one they use depends on a group of factors, as individual abilities, familiarity, as well as the available characteristics of the environment. Navigation strategies and activities are rich in diversity and adaptability [Golledge, 1999, Werner et al., 2000] in a range from global spatial knowledge to piloting using manifest cues [Arthur and Passini, 1992, Passini, 1984]. People may follow a path, learn to associate scenes with a particular action (e.g., turn left; [Schoelkopf and Mallot, 1995]), or might try to approximate a heading direction by choosing the path that most closely resembles this direction. The approach to more complex tasks requires the evaluation of the available strategies to reduce the number of elements that must be considered simultaneously and lighten the cognitive load.

In cases where rotational locomotion is involved the navigator benefits from combining strategies based on global spatial knowledge with those based purely local information (piloting, path-following). However, this combination is not always successful in terms of spatial knowledge updating. People use two different subsystems for spatial updating: (a) the direct egocentric one, that dominates, relies mostly on direct stimuli received from the environment, but when these are not available people use (b) mental representations, gradually constructed during their visuo-locomotive experience, and encoded in a viewpoint-specific way to long-term memory [Mou and McNamara, 2002, Presson and Montello, 1994]. Based on the fact that mental representations of different environments cannot be accessed simultaneously even if they are familiar for the user [Brockmole and Wang, 2002], we expect a delay after a rotation, or a cost in accuracy, especially if a decision points is following the turn. In the support of this claim, Waller et al. [2002] also suggest that updating mental representations after a turn is not automatic or obligatory as previously considered, but it rather requires a higher-level cognitive awareness of how the rotation affects the task at hand.

In case of revisiting a familiar environment, the user updates his location and his orientation with respect to the available surrounding elements (Fig. 1a - 1d). Two types of updates (i-ii) occur which correspond to the referred subsystems. The momentary egocentric self-to-object spatial relations, needed to control locomotion, are updated as long as there is perceptual support. This updating process is effective and requires minimal attentional control (although there must be limits on the number of objects monitored and on the self-to-object distance over which updating takes place). Egocentric updating (i) allows the observer to avoid obstacles, walk through on ways, etc. However, if the visual stimuli are insufficient (the location is either unmarked or out of sight) or the perceptual support is diminished, then the navigation ability depends on spatial memory. In that case, spatial updating rely on spatial information in the environmental subsystem that consists of keeping track of location and orientation with respect to the intrinsic system of reference used to represent the spatial structure of the environment. The environmental updating (ii) subsystem requires more attentional control than the egocentric updating.

## 2 FACTORS INFLUENCING VISUO-LOCOMOTIVE EXPERIENCE

It has been well documented that there is a number of factors affect the navigation performance of the user, such as level of familiarity, environmental characteristics, individual abilities or gender differences [Lynch, 1960, Sorrows and Hirtle, 1999, Winter et al., 2005]. In this chapter we are focusing on factors related to environmental aspects and the crucial role of familiarity with the environment:

### URBAN SPACE AND LARGE-SCALE BUILT-UP STRUCTURES

People frequently struggle with the task of navigating urban areas and the main reason is the complex structure and the dynamic nature of urban landscapes (they can be very crowded, with access restrictions or temporary changes), and it also involves moving between indoor, outdoor or transitional spaces (e.g. atriums, arcades, transportation hubs, foot tunnels or partially roofed halls). Built-up urban structures are referring mostly to indoor or transitional spaces and they are usually considered to be quite different from open urban spaces in terms of structure and properties but also in terms of how people perceive and navigate them. They differ in size and perceptual scale [Downs and Stea, 1977, Montello and Pick, 1993], or even dimensionally, meaning that in built-up space people move between different floors or levels whereas this is usually not the case for urban outdoor space. Staircases, for example, have the potential to negatively affect people's sense of orientation [Mastrodonato et al., 2013]. Another difference is related to the use of manifest cues and environmental features to facilitate wayfinding. Typical landmarks inside interior spaces differ from typical landmarks in outdoor environments, or the use of cardinal directions for the outdoor environment [Fontaine and Denis, 1999]. Due to the limited field of view in indoor environments, some useful landmarks available in outdoor environments such as the sun, mountains or water bodies, cannot be seen while inside buildings. Also the line of sight at indoor spaces is usually much more constrained than in outdoor ones.

However, it is not easily distributed urban spaces to outdoor and indoor built-up ones. As the visuo-locomotive experience in the city scape is continuous there are a lot of spaces that share properties/comprising indoor and outdoor areas, as well as locations, for which it may be difficult to decide whether they are indoors or outdoors (e. g. shopping malls, arcades and underpasses), public or not fully public, transitional or functional areas, and they may also include multiple traversable levels [Hölscher et al., 2006]. These areas are mainly the large-scale built-up structures such as train station, airports, shopping malls, airports, etc.

Navigating routes that span both types of spaces can be considered a significant challenge. Large-scale built-up structures often do not give access to global landmarks, reference directions, salient axes, or general coordinates. This is because these structures are larger than the sensory horizon of a user. As a result, the environment prevents navigators from perceiving the spatial structure at once and consequently from comprehending the environment as a whole. In other words, the navigator cannot make use of navigation strategies based on direct perceived information. Instead, spatial information has to be integrated across multiple places, paths, turns, for extended period of time [Poucet, 1993]. This can be considered fertile ground for alignment effect incidents and distortions on spatial representations.

### USER'S FAMILIARITY WITH THE ENVIRONMENT

The amount of previous exposure to an environment is a critical factor for user's visuo-locomotive experience, navigation performance [Holscher and Brosamle, 2012, Hölscher et al., 2006], and orientation [Gärling et al., 1983, Denis, 1997], but the methods to measure the degree of this influence are unclear. This exposure can take the form of a prior physical excursion in the environment, or an experience gained through visual representation aids (e.g. map); it can also be gained in a systematic conscious way or even in an unconscious way. The study of familiarity is complex and multi-dimensional, firstly because of the various modes of experience that includes [Thorndyke and Hayes-Roth, 1982, Appleyard, 1969], and secondly because of the fact that it contains non-spatial components such as feelings of warmth, safety, and security that complicate its meaning [Gale et al., 1990].

Navigation experience can be divided in terms of familiarity in two parts; one related to newcomers

[Denis, 1997, Raubal, 2001, Timpf and Frank, 1997] in an environment, and the other related to familiar users [Allen, 1999]. The latter is crucial for urban landscapes and the built-up urban structures, because except of the cases of a tourist or a person travelling to inexperienced regions, most of the ordinary people experience several wayfinding tasks in daily life, including finding a destination from a familiar place to another, or from a familiar to an unfamiliar destination within a region. The experience of familiar users critically differs from the unfamiliar ones, as they keep track of their orientation and location by a normally easy and reliable sensory integration process, even when visual cues are momentarily absent. Nevertheless familiar users still need to reorient themselves when they see a familiar environment from an unfamiliar perspective [Cornell and Heth, 2000]. In cases of complex built environments that involve ego-rotation and turns, increasing familiarity rate improves orientation tasks performance in accuracy and latency and make layout complexity less important [Bryant, 1982, O' Neill, 1992].

Rotational locomotion triggers the need for spatial knowledge update and the use of multiple reference frames, that requires cognitive flexibility for thinking about the same spatial information from different perspectives increases with increased experience, whether this experience is based on actual navigation or mentally derived from specific learning goals. Familiarity with landmarks may be ideal for navigation that involve turns, but when absent, people appear to recruit and use the information that is available, even when this requires switching perspectives [Bryant, 1982, Taylor et al., 1999, Thorndyke and Hayes-Roth, 1982, Foo et al., 2005].

### ENVIRONMENTAL ASPECTS

Navigation and specifically the cognitive part of it, the wayfinding, is recognised as an interactive process between users and the surrounding environment. Understanding the interaction and the limits are essential in order to develop predictive models of human behaviour. Even thought there is a lot of research on the aspects of mental representations and spatial knowledge updating from the perspective of cognition and mental imagery, such as the processes underlying and the characteristics of this abilities for humans, the role of the environment itself and its design have been mostly neglected [Dalton and Hoelscher, 2012]. However, a number of studies on this topic from 1970s [Best, 1970] until now, mostly on environmental psychology, indicate the importance of the layout complexity of the built-up space or the structure of the space [O'Neill, 1991, Weisman, 1981], as well as the appearance of the architectural space, the features that compose it (e.g. visual access, architectural differentiation, signage) [Arthur and Passini, 1992, Werner and Schindler, 2004, Sorrows and Hirtle, 1999, Winter et al., 2005]. Recent studies have also included analysis of airports (e.g., [Raubal, 2002], shopping malls [Dogu and Erkip, 2000] and universities [Abu-Obeid, 1998, Butler et al., 1993] in relation to the navigation performance of their users.

Natural or urban built-up environments differ in the information they make available for visuo-locomotion experience, or the information they provide for mapping and verbal description. For instance, built environments have more regular patterns, like straight lines and right angles. The major environmental characteristics that affect visuo-locomotive experience can be classified into two categories: the *environmental affordances*, and the *manifest cues* [Carpman and Grant, 2001]. Many research studies have put these two categories into completion to show which is the most effective one in different locomotive cases and in different locomotive tasks [Vilar et al., 2014]. The *environmental affordances* mainly refer to the environmental structure (e.g. floorplan layout, architectural geometry, brightness), and the *manifest cues* refer to signage and landmarks that elucidate the environmental structure.

Environmental affordances and manifest cues are both important for navigation when rotational locomotion is involved, as they address and correspond to different navigation strategies, and they are also related to different strategies for reorientation, maintenance of orientation or spatial knowledge acquisition and update. The manifest cues are the most prominent for navigation aid and for first-level orientation based on the scene. In the absence of observable featural cues at the scene, a navigator uses stored knowledge of his own orientation to establish a framework for coding his surrounding. Humans, as well as animals, seem to be sensitive to the geometric shape of their environment. The importance of geometric relations might be due to the stability of this information over time, compared to other featural cues whose appearance can change dramatically [Hermer and Spelke, 1996]. Additionally, the perceived spatial structure of an environment influences the way a space is mentally represented even in cases where the acquisition phase is well-controlled and the observer is limited to only a few views of the space [Shelton and McNamara, 2001, McNamara et al., 2003].

Spatial orientation research studies have been focused on two categories of cues to spatial orientation: geometric and featural cues [Cheng and Newcombe, 2005]. Geometric cues are provided by extended environmental surfaces, like the shapes formed by room walls or intersecting streets. Featural cues consist of non-geometric properties, such as colours and textures, which cannot be described solely in geometric terms. Natural scenes typically contain both geometric and featural cues. Experiments testing the relative contributions of these cues to human navigation commonly use a disorientation paradigm, suggest that the use of geometric cues during reorientation is nearly ubiquitous for humans, whereas the use of featural cues depends on participant age, environment size, and secondary tasks [Cheng and Newcombe, 2005].

Specifically for the cases of rotations in a navigation path, which are related to spatial updating, reorientation and maintenance of orientation, the common finding is that humans use of geometric cues during reorientation, whereas the use of featural cues depends on participant age, environment size, and secondary tasks. Rotational symmetry clearly influences reorientation performance in the combination with lack of architectural differentiation or when multiple orientations provide the same perspective of the space. Studies by Gallistel [1980, 1990] comparing different geometries of rooms, suggest that disoriented participants reorient by matching geometric properties of the perceived and remembered environments. In the case of maintenance of spatial orientation during self-movement, Kelly et al. [2008] showed that path integration is used to maintain a sense of conceptual "north" based on an perceived axis during self-motion, allowing for accurate matching between perceived and remembered environmental properties.

## 3 EMPIRICAL STUDIES IN ROTATIONAL LOCOMOTION: A MULTIMODAL METHODOLOGY

Most research on spatial knowledge update and reorientation has employed geometrically ambiguous environments for studying environmental structures and geometry, such as rectangular rooms contain diagonally opposite corners sharing the same geometric properties (the same angle and ratio of connecting wall lengths) [Kelly et al., 2008]. However, similar geometrical structures, involved in the large-scale built-up urban landscape, accommodate every-day navigation tasks with rotational locomotion. Using this environment for experimentation will provide a different overview of the holistic visuo-locomotive experience of users in respect to the aspects of familiarity and the range of available environmental cues. For instance, in the case of a train station, the structure is characterised by inherent homogeneity or symmetry (including the tracks and the gates), while at the same time the manifest cues (signage, labels, landmarks) follow a predefined logical rule set. Moreover, train stations are large scale built-up structure, that include public crowded indoor, outdoor and transitional spaces, as well as difficult to define space such as the roofed platforms near the tracks that can be considered part of the station but also outdoor space.

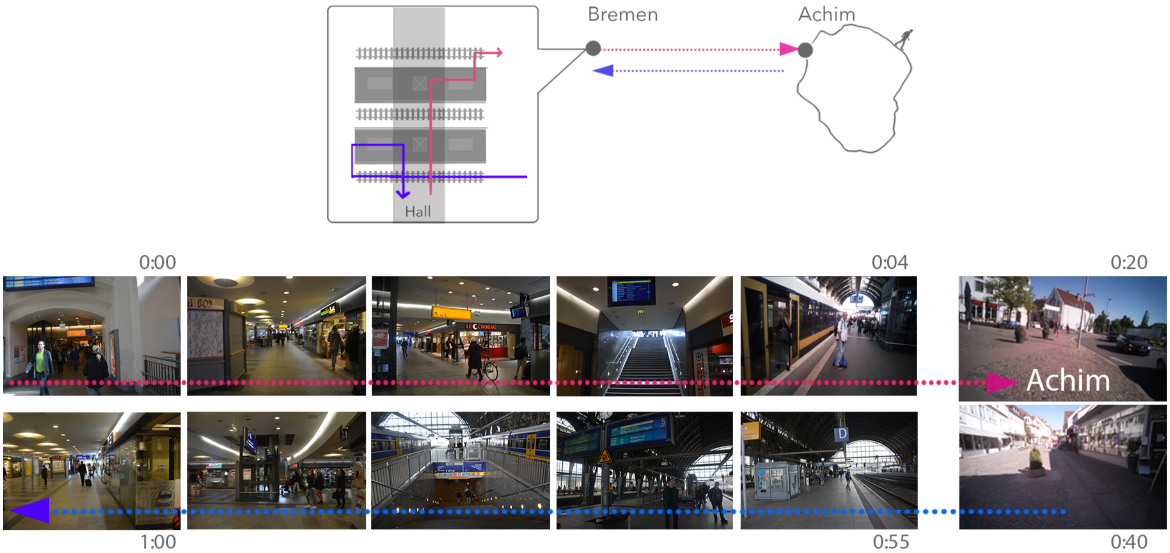
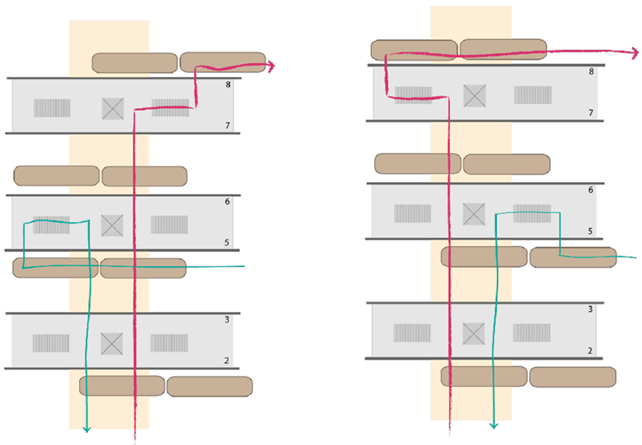



**Figure 2.** The navigation case study starts from the train station of Bremen and involves a trip to Achim and back by train, in a time range of an hour. The routes to the departure and the arrival platforms are chosen such that participants perform a rotation of 360° inside the station.

## A CASE STUDY AT THE BREMEN CENTRAL STATION

To study the navigation experience of users in large-scale buit-up structures, where the environment naturally leads users to rotate in space and frequently leads to "spatial updating" failure, we conducted a case study in the train station of Bremen (Germany) [Kondyli and Bhatt, 2018] (Fig. 2). Firstly, we are interested in investigating if regular commuters follow a particular navigation strategy, especially when rotation is involved, and on which environmental features this strategy relies on. Secondly, we investigate under which circumstances familiar with the environment users face momentary confusion events and if this phenomenon is related to the embodied rotation they perform during locomotion from the departure to the arrival position. Finally, as our motivation derives from Evidence-Based Design (EBD) we study human behaviour in reorientation circumstances in a real setting, where the stimuli are rich enough so that we can evaluate which environmental cues are more important than others at the level of scene observation or at the level of spatial knowledge updating and retrieval.

**Pilot Study Setup**. The case study took place in the main train station of Bremen (Germany) with 20 participants between 19-56 years old. The participants were divided into two groups according to their familiarity level (familiar-unfamiliar) with the train station, including a range of regular commuters to newcomers. Moreover the group of participants has been divided into two groups according to the navigation task they performed inside the train station by instructing them to use particular platforms during departure and arrival. Specifically, the path of the experimental group inside the train station includes 360 degrees angle of ego-rotation, while the control group, performs a rotation of 180 degrees (departing and getting back from the same direction) (Fig. 3). All the participants fitted with eye-tracking glasses, were asked to pursue a navigation task in the city of Achim (east outskirts of Bremen), that involves them leading the way from Bremen and back through the train stations and the train routes. The trip lasts overall an hour and the participants pursue a small wayfinding task in the urban space of Achim that is used as a cover story of the experimentation and as an indication of the individual navigation abilities of participants together with a follow-up orientation task. At the arrival of participants at the train station of Bremen, they disembark in a platform symmetrically opposite in the x and y axis (experimental group).



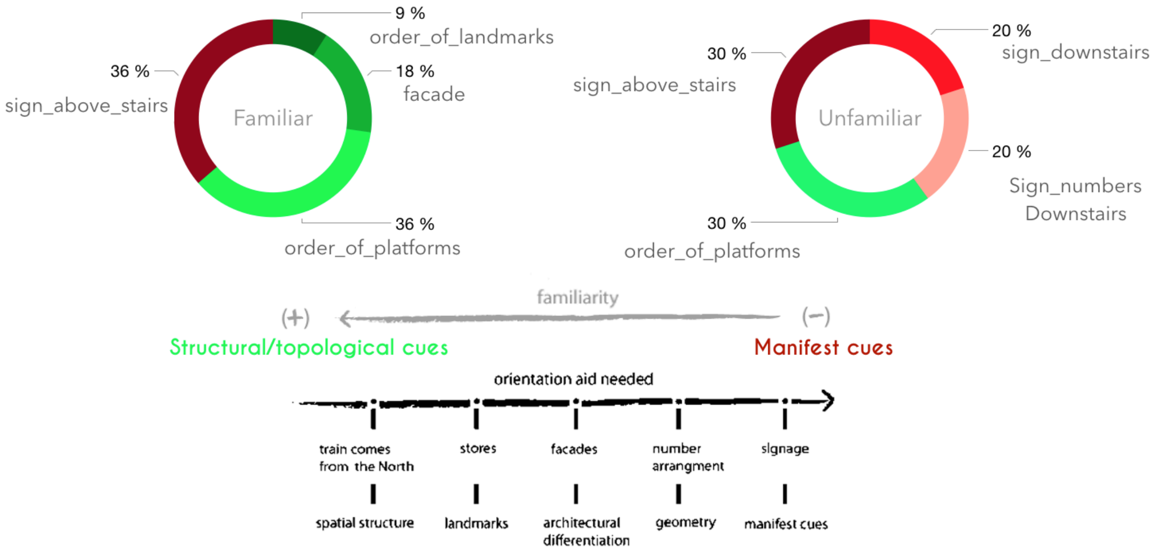
**(a)** Experimental group path **(b)** Control group path

**Figure 3.** The train-station platforms No. 8 and No.5 have opposite orientation, as well as the two staircases that participants use. The route of participants involves coming in from the railway station entrance leading up to the departure platform No. 8 South (red line), and from their arrival on platform No. 5 North to the exit of the railway station (green line). (a) the route of the experimental group that includes embodied rotation, and (b) the control group that exclude embodied rotation.

As a result, the participants experienced ego-rotation of 360 degrees angle between the departure and the arrival position.

**Multi-Modal Human-Behaviour Analysis.** We employ a range of sensors for measuring the embodied visuo-locomotive experience [Bhatt et al., 2016a,b] of users in the built environment: eye-tracking, egocentric gaze analysis (from video) and head movements analysis, camera-based visual analysis to interpret fine-grained behaviour (e.g., stopping, looking around, interacting with people), and also manual observations made by human experimenters, pre and post questionnaires, orientation task and sketch maps.[1] We suggest a combination of behavioural data analysis with morphological analysis of space and computational geometric structure analysis; that contribute to the systematic study of user-environment interaction, and in drawing conclusions about the impact of spatial features on users' experience [Bhatt et al., 2016b, 2014]. Specifically we combine qualitative and quantitative analysis of users' visuo-locomotive experience (visual attention patterns, signage detection, geometrical features detection, trace, walking pace, head rotation) together with the morphological analysis of the built environment (e.g. visibility graphs, isovist analysis, geometrical analysis, axial map), in order to evaluate people-centred design principles for large-scale public spaces that can be embedded into state of the art computer-aided design systems [Kondyli et al., 2017a,b]. Analysing the visuo-locomotive experience of users from empirical studies, using new generation tools (e.g. MindYourSpace [Bhatt and Schultz, 2017]) of behavioural analysis, can provide high-level semantic analysis of user's behavior with respect to calculation of the angle of rotation, number of turns, or by comparing the routes and the navigation performance of participants. Moreover, new cognitive assistive technologies also generate declarative

[1] For the orientation task participants were asked to point towards the direction of the starting position (the main hall of the train station) after the decision point of the stairs when they disembark, and also to provide a rate of confidence for their answer. The sketch-map task was a part of the post-questionnaire where participants were asked to draw their route inside the train station by adding information that they remember, such as the direction and the orientation of the platforms and the staircases they use, as well as the manifest cues that they recall.




**(a)** Navigation aid used by familiar or unfamiliar users

**(b)** Structural / Topological cues

**(c)** Manifest cues

**Figure 4.** Familiarity rate in relation to the available navigation aid of the environment. Case study at the train station in Bremen, Germany.

narratives of visuo-locomotive user experience from digital computer-aided architecture design (CAAD) based on this collected behavioural knowledge [Bhatt et al., 2014].

**Preliminary Results.** Preliminary results suggest that rotational locomotion aggravate the navigation performance and the sense of orientation after disembarking, for the overall group of participants, as unfamiliar and some familiar users experienced confusion events (e.g. stop, hesitation, look around, intensive visual search to both directions, etc.). Moreover it has been shown that unfamiliar and unfamiliar users rely on different environmental cues for navigation aid. Specifically, 35% of both groups perform confusion events during decision making after disembarking, while 90% of the experimental group declared lack of path integration abilities. For the analysis of the sketch maps 50% of the familiar and 60% of the unfamiliar users, as well as 70% of the of the experimental and 40% of the control group, presented an alignment effect considering the number and the direction of the turns their indicate for the route they pursue during the departure and the arrival at the train station. Moreover, 90% of the experimental group report lack of orientation and no path integration during disembarking, and they also report that they rely on the environmental cues for disorientation in the decision point. Specifically, familiar users tend to use more structural and topological cues (facades, order of platforms, order of shops) for reorientation that manifest cues (signage, labels, landmarks), while unfamiliar user stick to the available manifest cues, such as signage, landmarks, labels (Fig. 4). The fixations of the familiar used to the navigational aid cues from the environment that they use for reorientation, are few in number and duration, and ahead of time from the decision point on the stairs, while the opposite is true for the unfamiliar users who tent to explore the navigational aid environmental cues by approaching and descending the stairs.

### ESTABLISHING PRECEDENTS FOR BEHAVIOUR-BASED DESIGN SYSTEMS

In architectural and urban design the involvement of precedents in the design procedure is a common practice and it refers to the reuse of previous examples or rules from the design domain to authorise or justify a subsequent act of the same or an analogous kind. Precedents are used for assisting the design procedure from the stage of the concept until the final design decision-making. From our perspective, a precedent-based design assistance method [Kondyli et al., 2018] needs to ground design decisions on credible empirical studies, such as the case study at the train station reported in this research. For instance, extracting evidence about the environmental features that can be used as navigational aids from different user groups are necessary to establish precedents specialised for rotational locomotion cases. These precedents can be formulated as design suggestions or indications of the effects of environmental cues vis-a-vis rotational locomotion during navigation in built-up spaces differing in scale and functionality. Concerning the implementation, the precedents can be formalised (e.g., as design constraints) within state-of-the-art cognitive design assistance technology (e.g., [Bhatt et al., 2012, 2014]) or even within conventional design computing platforms; a model of these kinds of technological developments within parametric design technology has been recently demonstrated in [Kondyli et al., 2017b, 2018, Schultz et al., 2017]. With this pipeline, from the empirical studies to the expansion of the design system capabilities, we aim to contribute to people-centred design practice by providing, for instance, a large number of morphological alternatives (e.g., computed parametrically [Kondyli et al., 2018] or otherwise [Bhatt et al., 2012]) thereby ensuring human-centred design compliance in matters of navigation, wayfinding, and the overall visuo-locomotive cognitive experience [Bhatt et al., 2014].

## 4 DISCUSSION AND OUTLOOK

Behavioural analysis of rotational locomotion in navigation reveals that spatial representations undergo systematic distortions during the process of knowledge acquisition, encoding, decoding, storage, and retrieval. These distortions in spatial knowledge, are related to the environmental setting and they involve fragmentation, exaggeration, overlapping of elements, simplification, schematization, angle normalization, addition or omission of details etc. People use this spatial information on a perceptual level or a cognitive level to update their relative position if needed during their route. Featural cues (signage, landmarks, colour, lighting) are considered important for updating navigator's relative position as well as environmental structural, topological or geometrical cues, but their role is distinguished. Familiarity also play a significant role on the strategies used for navigation as well as on the preferred navigational aid environmental cues that are available.

Empirical studies about spatial knowledge updating when rotational locomotion is involved in a everyday navigation task provide insights about significant aspects of the underlying cognitive mechanisms and the implications on users performance. Such evidence based results on navigation in general, and rotational location in particular, present tremendous potential for people-centred (architectural) design [Bhatt and Schultz, 2017], and particularly for computational models of the cognitive visuo-locomotive experience analysis [Bhatt et al., 2014]. Using a case study in Bremen train station as an example of experimentation, we extract implications related to rotational locomotion in navigation and the environmental cues that should be considered in the design procedure of large-scale built-up structures. We suggest that a number of implications in navigation can be extracted based on empirical studies in large-scale built environments using a multimodal behavioural analysis approach [Bhatt et al., 2016b]; as one example, a formally modelled and computationally encoded specification of design precedents within parametric design tools may be consulted in [Kondyli et al., 2018, 2017b].

While lab-based experimental studies focus mostly on the cognitive mechanisms and the aspects involved in spatial knowledge acquisition and update, studies in real environments can focus on everyday tasks including all the spectrum of stimuli used for perception of space, the cognitive processes, as well as the aspect of proprioception and visual and auditory cues. However, further control experiments, for example in virtual reality (VR) settings, can contribute in discriminating particular aspects of the visuo-locomotive experience in relation to a range of environmental cues.

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