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Title
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Permalink
https://escholarship.org/uc/item/7328d4cj

Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 43(43)

ISSN
1069-7977

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Publication Date
2021

Peer reviewed

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Visuo-Locomotive Update in the Wild

The Role of (Un)Familiarity in Choice of Navigation Strategy, and its Application in Computational Spatial Design

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Abstract

We study active human visuo-locomotive experience in everyday navigation from the viewpoints of environmental familiarity, embodied reorientation, and (sensorimotor) spatial update. Following a naturalistic, in situ, embodied multimodal behaviour analysis method, we conclude that familiar users rely on environmental cues as a navigation-aid and exhibit proactive decision-making, whereas unfamiliar users rely on manifest cues, are late in decision-making, and show no sign of sensorimotor spatial update. Qualitative analysis reveals that both groups are able to sketch-map their route and consider path integration: i.e., conscious spatial representation updating was possible but not preferred during active navigation. Overall, the experimental task did not trigger automatic or reflex-like spatial updating, as subjects preferred strategies involving memory of perceptual cues and available manifest cues instead of relying on motor simulation and continuous spatial update. Rooted in the behavioural outcomes, we also position applications in computational modelling of navigation within cognitive technologies for architectural design synthesis.

Keywords: spatial update; familiarity; rotation; navigation; visuospatial cognition; naturalistic perception

MOTIVATION

Visuospatial cognitive processes underlying human navigation have been an object of inquiry from several standpoints (Montello, 2005; Weisman, 1981; Tversky, 2003). Studies investigating human (cognitive) strategies for navigation in diverse circumstances are abound; of key interest to this paper are spatial update and reorientation with spatial representations and/or external cues (Farrell & Robertson, 1998; Chen et al., 2017; Wang, 2017).

▹ **Embodied Multimodal Interaction** Naturalistic "in-the-wild" settings pose methodological difficulties typically not encountered in lab-based or clinical real/virtual environments. However, from an ecological viewpoint, the naturalistic method allows for investigating the multimodal confluence of environmental and individual characteristics in everyday activities at a level of embodied specificity and immersion that is not achievable in lab formats. This aspect is especially important for navigation tasks where the effect of physical movement on spatial updating as a result of sensorimotor representations and embodied interaction with the environment have been demonstrated (Santoro et al., 2017; Avraamides, 2003). We conduct a multimodal analysis in a real-world setting to provide a better representation of how different attributes influencing embodied navigation interact and affect visuo-locomotive strategies and decision-making.

▹ **Spatial Knowledge Acquisition and Update** The embodied visuo-locomotive experience of humans in large-scale built-up spaces, e.g., during a wayfinding task, encompasses a range of aspects including people's visual perception, their decision-making procedures and intentions, the affordances of the environment. A key aspect of visuo-locomotive experience relates to translational and rotational locomotion. Humans update their spatial representations, or use external cues for reorientation when needed. Spatial update strategies depend on situational factors, such as the availability of external sources of information (referring to environmental affordances/environmental cues, and manifest cues such as landmarks and signage) (Devlin, 2014), the familiarity with the environment, the cognitive demand involved etc. (Foo et al., 2005; Byrne & Crawford, 2010; Zhang et al., 2011; Li & Klippel, 2014). Extensive translation and rotation in the navigation path affects visuo-locomotive experience and resulting navigation performance (Presson & Montello, 1994; Kondyli & Bhatt, 2018).

▹ **Experimental Focus –and– Key Contributions** Our research investigates the role of spatial updating paradigms and models for interpreting navigation strategies in large-scale built-up environments in urban settings. We examine how different navigation strategies may be employed from users, and how these may change during the course of a navigation task in a real-world context. In particular, we focus on strategy adopted in relation to the familiarity (level) with the environment, as well as the difficulty of the task articulated via a *rotation metric* encapsulating a measure of the visuo-locomotive changes and ego-rotations encountered during a route, as well as the role of external visuospatial cues in spatial updating. The central questions addressed are: **Q1**. How does familiarity affect navigation strategies during active navigation?; **Q2**. How do environmental characteristics, namely rotational morphology of the path, turn direction, and visuospatial cues (environmental and manifest), influence the choice of navigation strategies and spatial update? **Q3**. How do navigation strategies mutually interact in a given context?

The broad-based agenda of this research culminates at the intersection of cognitive psychology, design, and engineering; this confluence, we posit and demonstrate, is necessary to translate basic behavioural outcomes into practical tools for the design and analysis of large-scale built-up spaces.

METHOD

We investigate the role of the environmental structure, the rotational locomotion involved in a path, and interaction with

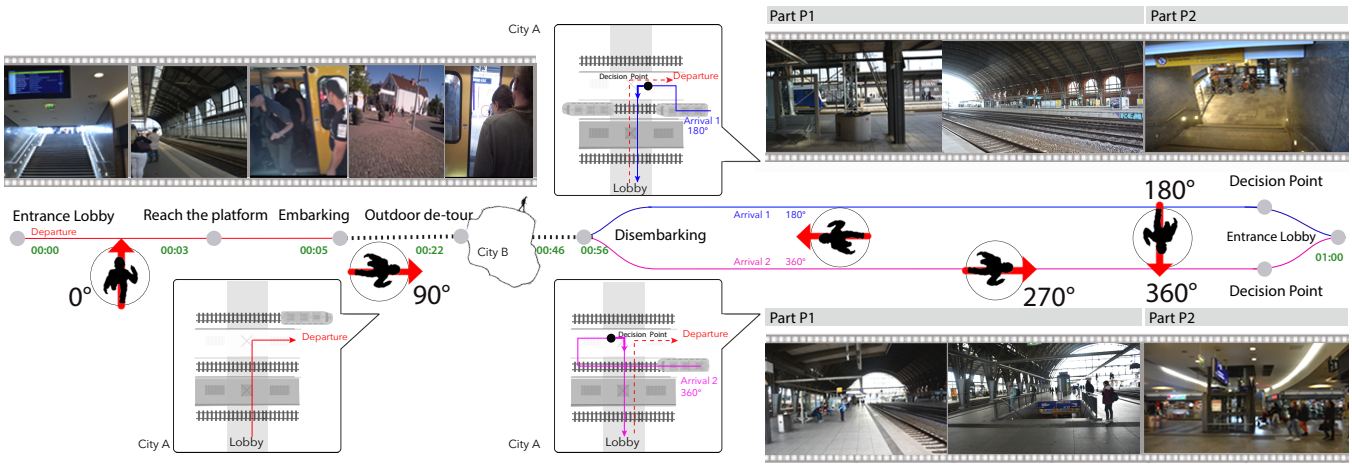


Figure 1: **Experimental Context**. The navigation path from the Entrance Lobby of the start train station (City A) to the destination city (B), and back. The departure route is common for all participants (one turn of 90°), while the arrival route differs in the rotation locomotion involved (180° or 360°), and it was accomplished by using two different train routes that disembark in different platforms and different locations in relation to the staircases. The participants' ego-rotation is calculated as the sum of the degrees they rotate to reach the starting point (Entrance lobby).

aspects influencing navigators' performance:

▷ **Context / Train Station and Railway trip** The experimental setting consisted of a (typical) train station in Germany. Each subject performed an everyday navigation task (lasting 50 mins to an hour) including determining a train to take (City A), reaching the platform, embarking on the train, proceeding to a target destination (City B), and after a short de-tour outside the destination train station, likewise returning to the start location (City A) (Fig. 1). Of specific interest was the part of the route from the point of disembarking from the train (Fig. 2a - **A**) during the return trip to the intersection/decision point (Fig. 2a - **E**) where participants had to decide to either *turn left or right* in order to return to the starting point at the entrance lobby. We define **Part P1** of the route as the part from disembarking from the train, then onto the platform, until reaching the staircase (i.e., **A**-**C**); and **Part P2** as the part from the beginning of the staircase until reaching the final intersection/decision point and making a turn at the underground passage (i.e., **C**-**E**). Both Parts P1-P2 have a number of navigation-aids similarly distributed and accessible to all participants. Additional cues of the dynamic scene known to attract attention in naturalistic tasks (Foulsham et al., 2010; Fotios et al., 2015), e.g., unexpected events involving people, avoiding obstacles, are not considered in this analysis and only those data-points have been considered where such factors do not exist.

▷ **Experimental Setup** Post quality control, we analysed data of 20 adult participants: 11 female and 9 male, with ages in range 19-56. All participants had normal vision, were tested individually, and did not participate in more than one study. Participants were divided based on a pre-questionnaire into two groups: 10 **familiar** and 10 **unfamiliar** subjects. Unfamiliar participants were considered the ones who had never been in the train station before or who had used it only once to arrive to the city. Familiar users were considered subjects who either commuted by train in a daily basis, or used to commute regularly by train in the last two years, or used the train station more than once per month for the last two years. However, none of the participants was commuting from City A to City B in a regular basis. Within each group, participants were equally distributed to follow one of two routes differing in an ego-rotation angle of either 180° or 360° (Fig. 1). A *between-subjects* design for analysing familiarity levels and the range of rotational locomotion was used. Protocol ensured is: **(1)**. participants were instructed at the spot to embark to the next train available with destination City B. No previous training or further instructions were given. The two different routes were distinguished by the time session distributed to the participants according to the railway schedules and the platforms used in each case; **(2)**. sessions were performed during (summer) daytime with uniform lighting and other conditions; **(3)**. timing and overall duration sessions was the same across participants lasting approx. one hour, and starting from the entrance lobby few minutes before the departure time of the train in both directions to ensure uniform conditions, e.g., environmental exposure; **(4)**. participants conducted non-relevant outdoor task at the destination city aiming to divert attention from the navigation inside the train station and maintain engagement; and **(5)**. the experimenter never distracted/assisted participants. After the navigation task a freehand sketch-map task was carried out, in which participants were instructed to reproduce the route they followed inside the train station for the departure and the arrival as accurate as possible in a blank sheet.

▷ **Multimodal Behaviour Analysis** The multimodal analysis combines behavioural (e.g. gaze patterns, visual range, areas of interest - AOIs) and objective measures (e.g. number of fixations, duration of fixations, 1st fixation on AOI) on visual attention through the mobile eye-tracking that partici-

pants wore, together with the results of the post-questionnaire and the sketch-map on spatial updating and navigation strategies, and finally, notable insights from qualitative data. Approximately, four hours of video recordings from the egocentric video and the eye-tracking were annotated and analysed focusing on the navigation path (departure and arrival) inside the train station in City A (Fig. 1). Visuospatial cues were annotated and categorised into manifest cues (e.g. shop sign, exit sign, city direction sign, map, attention triangle sign, destination info sign) and environmental cues (e.g. elevator, brick facade, glass facade, staircase, platforms, outdoors, rails, shops) for the two parts of the route (P1, P2). These were used as areas of interest (AOI) for the annotation of fixations. Confusion events –(e.g. re-route, ask for help, multiple head movements, hesitation, stop)– were annotated based on head movements, changes in direction, speed and audio cues. The experimenter, was non-invasively following each participant for the entire run, also recorded observations concerning confusion events. A post experiment questionnaire and a sketch-map task were performed in order to evaluate navigation strategies and participant's memory of visuospatial cues used as navigation-aid. The sketch-map evaluation was based on the accuracy of the route line (e.g. number of turns, direction of turns during departure and arrival), while accuracy on landmarks and signage positions was not analysed as they were not requested from the participants.

RESULTS

Results based on a multimodal analysis of subject behaviour are as follows **(R1–R4)**:

R1. (Un)Familiarity vis-a-vis cue selection

► Familiar navigators rely on environmental cues whereas unfamiliar navigators utilise manifest cues instead during active locomotion.

Familiar participants spent more time fixating on environmental cues than on manifest cues, whereas unfamiliar participants exhibited the opposite pattern (Fig. 2c). Specifically, there was a significant interaction between the familiarity level (familiarity, unfamiliar) and the type of navigation-aid cues (environmental and manifest cues) for the part P1 concerning the fixation duration [$F(1, 15) = 6.19$, $p = 0.025$]. However, the frequency of fixations did not differ significantly between the two groups. These results coincide with the outcome of the questionnaires concerning the navigation strategies that the two groups reported to use: 65% of familiar participants used environmental cues as navigation strategy, and 70% of unfamiliar participants reported manifest cues instead. This difference between the two groups was not so distinctive in Part P2 (closer to the decision point, Fig. 2a). A factorial ANOVA on fixation duration for navigation-aid cues for P2 in relation to familiarity and navigation-aid cue category showed no significant difference [$F(1, 15) = 0.65$, $p = 0.433$] (Fig. 2b). Moreover, familiar users reported that they combined manifest and environmental cues at this part of the route. For instance, many familiar participants used the descending platform numbers as an indication of the direction towards the station's entrance lobby. This is in accordance with the adaptive combination theory (Newcombe & Huttenlocher, 2007) suggesting tendency to combine available features, in this case the structure of the building, the platform's enumeration and the signs, however, this was not the case for unfamiliar participants.

R2. (Un)Familiarity wrt. choice & timing of navigation strategy

► Familiarity influences the choice and timing of navigation strategy application. Familiar navigators were proactive in detecting visuospatial cues before reaching the decision point thereby avoiding confusion at the decision point; unfamiliar users detect cues relatively closer to the decision point. This difference is also reflected in the navigation strategies the two groups employ.

Even though 80% of familiar and 100% of unfamiliar participants responded that they did not know the correct direction during disembarking from the train (showing failure in automatic, or reflexlike spatial update), familiar participants seem to have deployed a successful navigation strategy before reaching the key decision point, while this was not the case for the vast majority of unfamiliar navigators. We recorded 40% fewer confusion events (e.g. stop, look around) for familiar than for unfamiliar users at the key decision point (Fig. 2a – Point D). Specifically, 80% of familiar participants reported having performed consciously spatial updating after disembarking, either by using the available external visuospatial cues, or by combining them with an enduring representation (e.g. egocentric snapshot, structural representation) in an egocentric-update and reload strategy in Part P1 of the route. The other 20% of familiar participants were unable to explain their strategy that might imply an unconscious spatial updating. Unfamiliar participants reported conscious decision making using manifest cues as a navigation strategy (90%).

The gaze analysis during Part P2 of the path close to the key decision point confirmed the proactive behaviour of familiar navigators. Specifically, on Part P2 —defined from the staircase to the key decision point— participants have visual access towards two main signs one after the other at the centre of the scene along their path; one above the staircase – S1 (Fig. 2a point C), and a second in front of the elevator which is visible at the end of the staircase –S2 (Fig. 2a point D). By measuring the time when the participants first detected the sign, if they did, in relation to the moment when the sign first appeared in the scene, we predict how likely it is for the sign to get detected according to the familiarity level and when. The cumulative probability plots (Fig. 3a-3b) show that it was more likely for familiar navigators to detect quicker the signs, while the unfamiliar ones were more likely to detect the sign in due time as they were approaching the decision point. Specifically, concerning the sign at the elevator (S2), it was more likely for the familiar navigators to detect it in the first 2 secs when it first appeared, but it was more likely overall that the unfamiliar ones would fixate

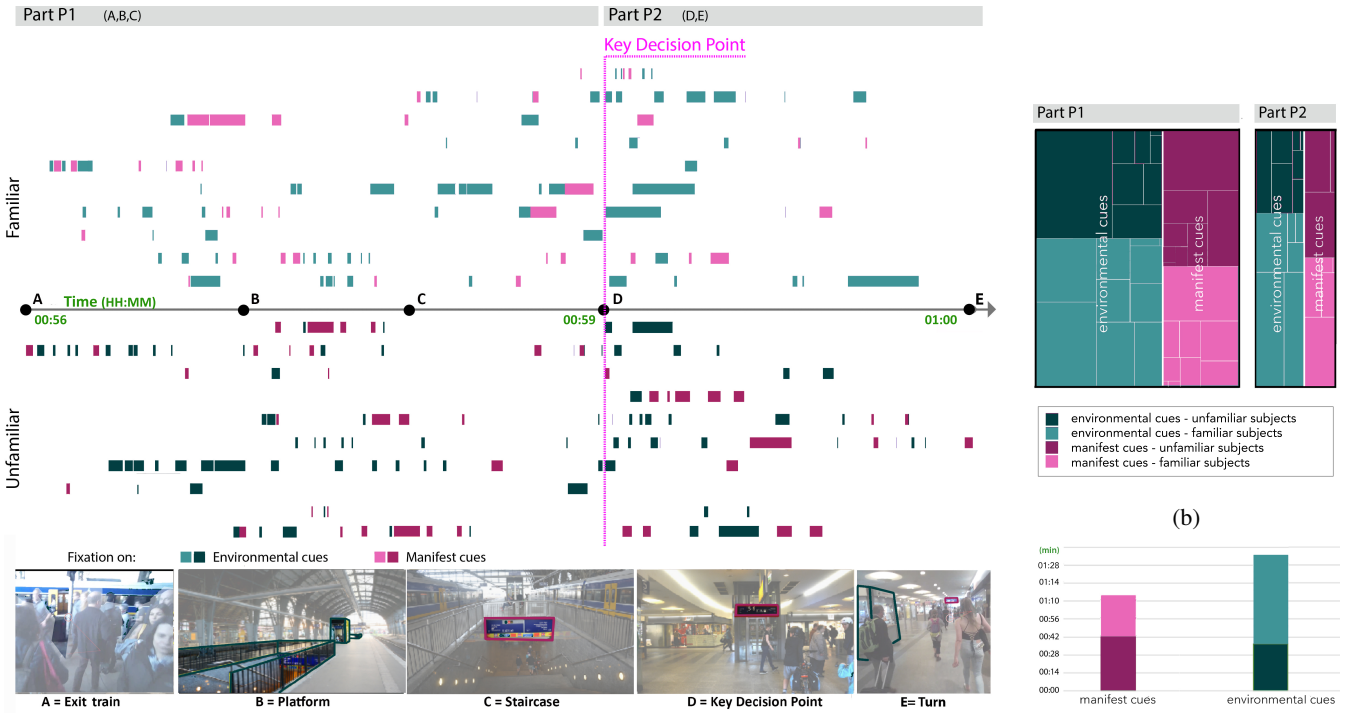


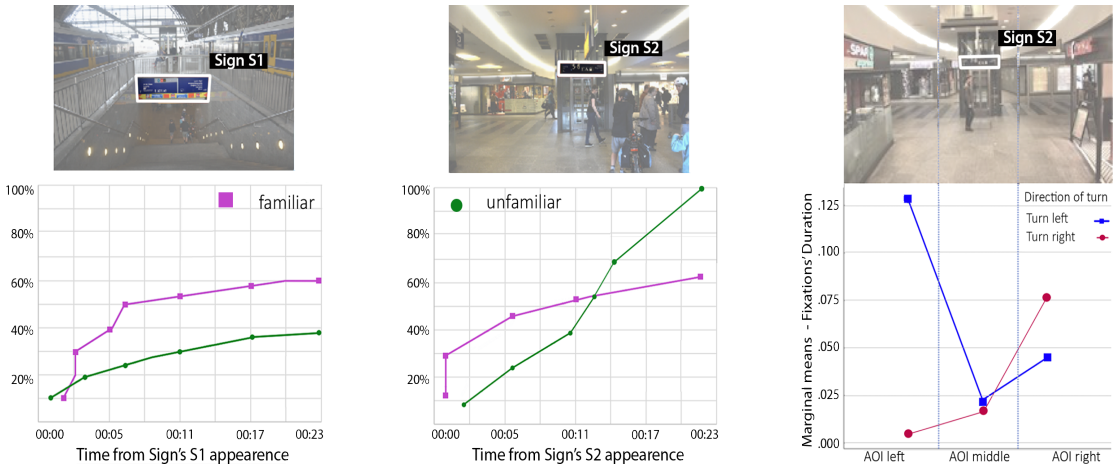
Figure 2: **(Un)Familiarity and Attention to Cues** (Path Parts P1-P2): **(a)** Frequency and duration of fixations on cues along the experimental route coded over time. Each line represents the fixations from one participant (saccades between fixations were not considered at this stage). We normalize the data to bring all the variables to the same time range, and arrange them based on the key decision point. The time points in the figure are indicative; **(b)** Distribution of fixation duration on environmental and manifest cues in the two parts P1-P2; **(c)** Overall fixation duration recorded for both parts P1-P2 for the sum of participants as per the navigation-aid cues. The colours follow the legend in (b).

on it. The cumulative probability suggests that both signs were probable to be detected by familiar participants quickly while unfamiliar ones tend to have a more exploratory gaze behaviour until reaching the key decision point. However, we note that gaze analysis showed that 40% of familiar participants fixated on the sign S1, even if they did not report to use it as a strategy, while 20% of familiar participants did not fixate on S2 but they reported using it. This shows that gaze patterns do not always correspond to the reported answers concerning the navigation strategies. We hypothesise that familiar navigators could be either utilising their peripheral views, or using signs for verification purposes (without reporting the same in the qualitative study); this is an aspect requiring further investigation.

R3. Direction of movement vis-a-vis gaze behaviour

▸ Direction of movement at a decision point guides gaze behaviour despite the familiarity level of the navigators. Closer to the decision point, navigators gaze towards the direction they will follow; turning left attracts more intensive attention.

Analysing gaze behaviour in Part P2 of the path close to the decision point, we notice that familiarity did not have a prominent role in gaze allocation at this part, while the direction of movement at the decision point, meaning the direction that people turned (left, or right turn) at the intersection, was the most important impact factor. We divided the symmetrical scene while approaching the decision point of the intersection using the vertical axis in the middle of the elevator to define as AOIs the right and left, and the middle part based on the width of the elevator containing sign S2 (Fig. 3c). We used a repeated measures MANOVA to examine the effect of familiarity (levels: familiar, unfamiliar) and direction of movement (levels: turning right/left) on the duration of fixations for the defined AOIs (left, middle, right). The results showed a correlation between the direction of movement and the fixation duration patterns [$F(1,16)=4.14$, $p=0.035$], but no significant correlation between the familiarity levels [$F(1,16) = 0.59$, $p = 0.561$]. These results support previous studies suggesting a systematic bias of gaze towards the direction that people imminently follow (Wiener et al., 2012). Moreover, participants who turned left had in overall a greater duration of fixations before they turned, than participants who turned right (Fig. 3c). Taking into consideration the existence of a rightward attentional bias for extrapersonal stimuli (Robertson et al., 2015), we can conclude that it is more natural for the participants to turn right, while participants who had to turn left needed more focused attention beforehand.



(a) (b) (c)

Figure 3: **(a-b)** Cumulative probability of signs S1 and S2 to be fixated over time in relation to (un)familiarity; **(c)** Estimated marginal means of fixations duration in relation to the direction of movement at decision point (scene is divided into three AOIs: left, middle, and right).

R4. Rotational locomotion and its effect on spatial updating

▸ Extensive rotations in the navigation path aggravate spatial updating performance.

Previous studies suggest that rotational locomotion aggravates the navigation performance (Kelly et al., 2008; Presson & Montello, 1994). The behavioural analysis of our study showed no significant interaction between the navigation performance and the angle of the rotational locomotion. However, the effect of rotational locomotion was prominent on the sketch-map task, where updating of spatial knowledge representations was required. Participants who performed 360 degrees ego-rotation (instead of 180 degrees ego-rotation) recorded 30% more errors when asked to reproduce an accurate map of their route, regardless of their familiarity level. We suggest that the reason for no significant effect of the rotational locomotion on active navigation performance was that even if participants did not effectively update their spatial representations, they switched from path integration strategies to strategies that incorporate external visuospatial cues to mitigate the loss of orientation, and successfully coped with the navigation task. The use of the relevant strategy was indicated by the post-questionnaires and the comments that the subjects made during the sketch-map task, where they orally revealed details on the use of path integration, or manifest and environmental cues during the navigation task. A number of their claims were also confirmed by the fixations data; e.g. participants confirmed of using the sign above the stairs for reorientation after disembarking and we also annotated fixations on Sign 1 for the same subjects. However more data are needed to investigate this direction.

DISCUSSION AND RELATED WORK

We discuss key results (**R1–R4**) vis-a-vis the state of the art on the influence of (un)familiarity on spatial update from the viewpoints of (embodied) active task performance, reorientation, and rotational location:

▹ **Active Task Performance** Past research suggests that navigators were able to perform spatial update using path integration, static (e.g. allocentric cognitive map, egocentric snapshots) or dynamic representations (e.g. egocentric updating) (McNamara, 2017; Wang, 2017). When physical movements and sensorimotor encoding were present, humans can also perform effortless automatic spatial update (Avraamides, 2003). However, the current study shows that *during active locomotion* in a naturalistic everyday navigation task where a full-range of combined perceptual and cognitive processes are involved, subjects do not demonstrate spatial updating strategies based on path integration, or enduring spatial representations, instead explicitly relying on external visuospatial cues. However, note that: (1). people are still able to perform well in spatial updating when they are explicitly asked to (in the sketch-map task); and (2) some familiar users do perform an egocentric-update and reload strategy with an enduring egocentric or allocentric component (e.g. structure and enumeration of platforms).

Relevant research work from neuroscience shows that the increasing demand of resources needed for both the cognitive and motor systems, resulting in Cognitive-Motor Interference (CMI) and can undermine a cognitive task as for example the impact of walking on the parallel processing of visual stimuli (Nenna et al., 2020). Additionally when the task gets more difficult, e.g., as a result of rotations in the path, a symmetrical environment or even lack of familiarity, the confluence of these attributes is reflected on the preferred navigation strategies from participants. We conclude that automatic strategies and enduring mental representation strategies for update are indeed possible, but undermined by the reality of everyday tasks and the limits of working memory, especially when environmental visuospatial complexity is high.

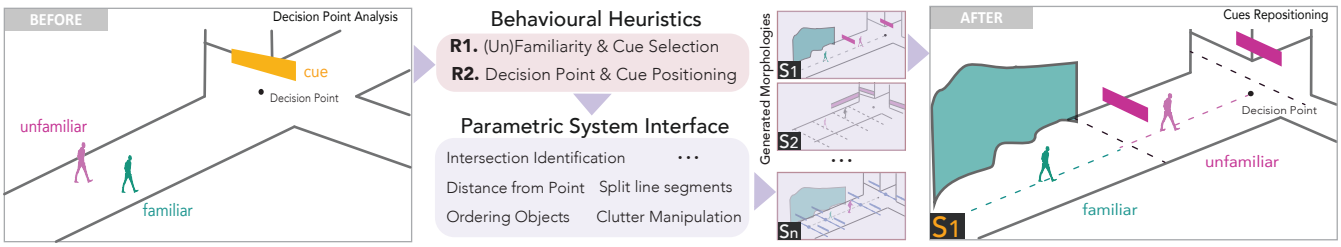


Figure 4: **Behavioural Heuristic Driven Visuo-Locomotive Experience Planning**. Navigation-aid cue positioning based on R1 and R2.

▷ **Reorientation** This study confirms previous findings, e.g., Li & Klippel (2014); Weisman (1981), on the significance of familiarity on navigation performance and its predominant role on spatial knowledge update, particularly that navigators with different familiarity levels employ different navigation strategies, detect and use different visuospatial cues in different parts of the route. Waller & Hodgson (2006) suggests familiarity reduces the effect of disorientation on egocentric updating process, as long as spatial representations can be retrieved from long-term memory. In our study, familiarity did not prevent disorientation during active locomotion, and also, even if spatial representations could be retrieved for the sketch-map task they were not used as a navigation strategy by familiar users. However, familiar participants performed better at navigation with less confusion events as they were able to address their disorientation before reaching the decision point.

▷ **Rotational Locomotion** Although familiarity enhances navigation performance even if spatial reorientation is needed, in our study familiarity did not mitigate the effect of extensive (visuospatial) complexity of the navigation path –as introduced by the *rotation metric* factor– shown in the sketch-map task performance of familiar participants. This result is in line with previous work on the impact of ego-rotations on human orientation, and its importance for navigation performance (Kelly et al., 2008; Presson & Montello, 1994). Specifically, experiments on relative precision of transient and enduring representations show that switching between representations does not require disorientation, but can also be produced by ego-rotations as small as 135° (Waller & Hodgson, 2006). These examples show that people are able to use motor simulation strategies, and perform continuous transformations on spatial representation for spatial updating where rotations are involved and if the task affords it (Zacks, 2008), meaning that spatial updating does not necessarily operate holistically, and it can be unreliable as a result of a cumulative rotational angle of the path.

APPLICATION / DESIGN COMPUTING

Behavioural outcomes pertaining to spatial cognition need to be integrated within assistive design technologies aimed at empowering specialists, e.g., in space planning, computer-aided design, post-occupancy-analysis-based redesign (Bhatt & Freksa, 2015). Driven by this need for the real-world applicability of behavioural outcomes, ongoing work aims to develop a general methodology to formalise and integrate heuristics pertaining to human-behavioural precedents –e.g., as interpreted from results such as **R1–R4**– within computer-aided architecture design (CAAD) systems. Figure 4 illustrates an implemented concept of this line of work in the context of Parametric CAAD systems (Woodbury, 2010; Kondyli et al., 2021): an example of human behavioural heuristics deriving from the current behavioural study, and specifically the results R1 and R2 on (un)familiarity, cue selection, and distance from decision point; are translated to a formal semantic representation, and subsequently geometrically interpreted via a set of high-level operations corresponding to the interface of a parametric system. This in-turn (generatively) results in diverse morphologies (e.g., S_1–S_n; Fig. 4) corresponding to prototypical design instances that become candidate solutions meriting further analysis by a designer. Specifically, the results of R1 and R2 can be translated as design indications such as: the positioning of environmental and manifest cues should be related to the familiarity level of the visitor, and so environmental cues which are mostly directed to familiar users should be positioned along the path in distance from the decision point, while manifest cues mostly useful for unfamiliar visitors should be positioned closer to the decision point. By encapsulating this knowledge to a parametric component, the tool can analyse a navigation path in a design interface, deconstruct it into segments and decision points, calculate the distance ahead of each decision point and suggest positions of environmental and manifest cues accordingly to address the needs of various visitors.

OUTLOOK / BEHAVIOURAL CONTEXTS

Supplementary studies —with a similarly naturalistic setting and multimodal analysis method— are necessary (and planned) to further expand the scope of presently obtained results. We believe that hospitals, airports and other large-scale public spaces would be ideal test-beds; our own research pursues hospitals and museums as a next step. More broadly, our outlook is motivated by the fact that a majority of research in human navigation is typically conducted in highly controlled lab-based or virtual reality settings. We posit that there is a need in spatial cognition research, and navigation studies in particular, to operate under ecologically valid naturalistic conditions, and establish corresponding open datasets and experimental benchmarks for ensuring the technological uptake and real-world application of evidence-based studies.

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