Route Planning with Transportation Network Maps: An Eye-Tracking Study

Elise Grison[12*], Valérie Gyselinck[2], Jean-Marie Burkhardt[2] & Jan Malte Wiener[3 4]

[1]Memory and Cognition Lab, UMR S894, Paris Descartes University and INSERM

[2]Psychology of Behaviour and Mobility Lab, IFSTTAR

[3]Psychology Department, Bournemouth University

[4]Dementia Institute, Bournemouth University

[*]Corresponding author: Elise Grison

e-mail: eligrison@gmail.com

Telephone: +33179532986

Acknowledgments

This study was carried out thanks to a grant for two months international exchange from the Paris Descartes University Doctoral School (ED 261, *Cognition, Comportements, Conduites Humaines*).

Abstract

Planning routes using transportation network maps is a common task that has received little attention in the literature. Here we present a novel eye-tracking paradigm to investigate psychological processes and mechanisms involved in such route planning. In the experiment, participants were first presented with an origin and destination pair before we presented them with fictitious public transportation maps. Their task was to find the connecting route that required the minimum number of transfers. Based on participants' gaze behaviour, each trial was split into two phases: (1) the search for origin and destination phase, i.e., the initial phase of the trial until participants gazed at both origin and destination at least once, and (2) the route Planning and Selection phase. Comparisons of other eye-tracking measures between these phases and the time to complete them, which depended on the complexity of the planning task, suggest that these two phases are indeed distinct and supported by different cognitive processes. For example, participants spent more time attending the centre of the map during the initial Search Phase, before directing their attention to connecting stations where transitions between lines were possible. Our results provide novel insights into the psychological processes involved in route planning from maps. The findings are discussed in relation to current theories of route planning.

1. Introduction

Imagine visiting a big city like London or Paris for the first time. After your arrival you decide to use public transportation to get to your hotel. If you do not know the city, you are likely to use a map of the transportation network. First, you will need to find your current location (for example the train station) as well as your destination (the hotel). Then, you will have to identify possible routes from your current location to the destination and choose the one which suits you best.

Planning a route to reach a specific destination is a common wayfinding task (Farr, Yarlagadda & Mengersen, 2012; Golledge, 1999). Route planning, which can be conceptualised as a problem solving task (Gärling, Säiä, Book & Lindberg, 1986; Hayes-Roth & Hayes-Roth, 1979), has been proposed to be comprised of three phases (Brunyé, Mahoney, Gardony & Taylor, 2010): First, reviewing the spatial relationship between an origin and a destination; second, identifying and comparing possible route options; and third, selecting the most viable path (see also Bovy & Stern, 1990; Gärling, Lindberg & Mäntylä, 1983; Golledge, 1995). As far as we know, however, no study has experimentally validated and confirmed the existence of these phases. Instead, route planning studies have mainly focused on strategies adopted by people to identify, compare or select a route. Consequently, little is known about the cognitive and visual processes involved in the different phases of route planning, particularly when planning with transport network maps.

The main objective of the current study is to develop a better understanding of how people search, compare and select between possible routes in transportation network map. To do so, we developed a novel eye-tracking paradigm.

1.1. Route planning with map

The first phase of route planning involves the search of origin and destination as well as developing an understanding of their spatial relationship. When planning routes from maps, this phase begins by a visual inspection of the map. Indeed, road maps, building maps or network maps are visual representations of a delimited space from a "bird's-eye" perspective, providing information about spatial relationships between places (Casakin, Barkowsky, Klippel & Freska, 2000; Meilinger, Hölscher, Büchner & Brösamle, 2007). When searching for the locations of the origin and the destination in a map, navigators engage in a classical visual search task (with two targets), a process which has been extensively studied in other contexts (see for example Hendersen, Weeks & Hollingworth, 1999; Neider & Zelinsky, 2006; Sobel, Gerrie, Poole & Kane, 2007). These studies have shown that visual search is strongly influenced by the number of distractors and participant's knowledge about the target, resulting in more efficient search if participants are familiar with the target (Beck, Trenchard, van Lamsweerde, Goldstein & Lohrenz, 2012; Wolfe, 1994). It has also been shown that the visual quality of the map (i.e., more or less cluttered) can influence visual search. For example, Beck and al. (2012) asked participants to search for elevation markers indicating the altitude of the terrain while manipulating the amount of visual clutter. Participants were either familiar with the target (e.g., pilots) or not (e.g., students). While visual clutter resulted in less efficient search, this effect was reduced in participants familiar with the target.

Experimental studies addressing the second and third phase of planning a route, i.e. identifying and comparing options and then selecting the most viable one, have mostly concentrated on the strategies used to identify a suitable solution. Visual versions of the Traveling Salesman Problem (TSP) are particularly suited to investigate strategies involved in the planning of complex multi-stop routes. In a typical experiment, participants are presented with a number of locations represented by simple dots on a map or a computer screen. They are then asked to connect these locations with straight lines such that the resulting path is optimal with respect to its overall length. Several strategies have been identified and there is an on-going debate regarding which strategies participants apply in such visual TSPs (for an overview, see MacGregor, & Chu, 2011; Wiener & Tenbrink, 2008). The *Convex hull method*, for example, states that the first planning step produces a tour that encompasses all external dots. The remaining internal dots are added in later planning steps (MacGregor & Ormerod, 1996; MacGregor, Ormerod & Chronicle, 1999; MacGregor, Chronicle & Ormerod, 2004). The *Hierarchical nearest neighbour* method is a different planning heuristic which assumes that clusters of targets are established in the first step and routes are planned within these clusters. In a second step the clusters are then linked together into a tour (Vickers, Lee, Dry & Hughes, 2003). Although the TSP task is different from situations in which users have to plan a route between only two locations (e.g., MacGregor et al., 2004; Wiener & Tenbrink, 2008), these studies demonstrate the use of strategies or heuristics to reduce the cognitive effort associated with route planning, i.e., the identification of and selection between alternative routes.

The second phase of route planning (i.e., identification of path alternatives) has received little attention in studies investigating route planning from maps between only two locations. Indeed, in most studies participants are presented with path alternatives that are already highlighted in the maps and are asked to choose between them. This corresponds to the third phase of route planning (i.e., the selection of one alternative) and several strategies explaining biases in such route selection have been described (Gärling & Gärling, 1988): The *Initial segment strategy*, for example, states that participants, when choosing between equally long alternatives, prefer routes that feature the longest initial straight segment, presumably as this route initially reduces the distance to the destination faster than the alternatives (i.e., Bailenson, Shum & Uttal, 1998; 2000). When asked to choose between a southern and a more northern route, participants show a reliable preference for the southern route (Brunyé et al., 2010). This preference, which has been replicated in various countries, is likely to result from the misconception of increased elevation to the north (*North is up(hill)*: Brunyé, Andonova, Meneghetti, Noordzij, Pazzaglia, Wienemann, Mahoney & Taylor, 2012; Brunyé, Gagnon, Waller, Tower-Richardi & Taylor, 2012).

1.2. Gaze behaviour and visual processing of maps

The analysis of gaze behaviour during route planning from maps is a promising mean to develop a better understanding of the underlying visual and cognitive processes. Brunyé and Taylor (2009) used eye-tracking to study map exploration and learning. After exploring maps for five minutes, participants were asked to draw the maps and verify statements about landmarks. During visual exploration, participants tended to first inspect the central region of the map before moving on to peripheral regions.

To our knowledge, little research has addressed how path planning and selection (i.e., identifying and comparing route options and choosing the most viable path) is reflected in gaze behaviour. Cazzato, Basso, Cutini and Bisiacchi (2010) recorded gaze behaviour to investigate strategy use and strategy switches during path selection. They asked participants to solve a visual version of the classical TSP. Gaze behaviour analysis demonstrates that strategy switching during a trial result in an increased number of fixations. One interpretation of these findings is in line with this cognitive load literature which suggests that strategy switches during a task are more cognitively demanding than maintaining the same strategy. **Other studies investigating the relationship between cognitive load and gaze behaviour showed**

that increased cognitive load resulted in more fixations, smaller saccade amplitudes, and larger pupil size (Just & Carpenter, 1976; Pomplun, Reingold & Shen, 2001;Van Orden, Limbert, Makeig & Jung, 2001).

1.3. Route planning in transportation networks

As reviewed above, most literature on route planning from maps used road or building maps. Network maps, however, are structurally different to road or building maps. They are typically composed of three types of information: segments representing lines, points representing stations (with station name) and transfer points representing connections between lines (Guo, 2001). Network maps are designed according to several rules (i.e. *Beck rules*: straight lines, absence of street details, restricted number of angles permitted; Roberts, 2008). While these rules simplify the information presented and therefore the comprehension of the map, they also result in topographical distortions (Guo, 2011, Roberts, Newton, Lagattolla, Hughes & Hasler, 2013). Despite these simplifications, network maps have a reputation to be difficult to understand. In particular, nodes between lines or transports modes are often not well represented and can be interpreted wrongly (Guo, 2011). Accordingly, most research in the area focused on design principles in order to improve the understanding of transportation network maps (Casakin & al., 2000; Freksa, 1999).

A few studies have focused on how the design of network map affects performance in route-planning task (Garland, Haynes & Grubb, 1979; Guo, 2011; Robert et al., 2013), but so far, little research has studied the cognitive and visual processes involved in route planning from transport network maps. We propose that route planning using network maps has different requirements than route planning from route or building maps. First, there are often dozens of stations and, given little advanced knowledge about the transportation network, the first phase of route planning, i.e., the establishment of the relationship between origin and destination, requires localising these two locations first. This is a visual search task which is not required in either TSP problems where all locations are targets (MacGregor & Ormerod, 1996; MacGregor et al, 2004) or in route choice from maps studies where origin and destination are either highlighted or learned before testing (Bailenson et al., 1998; Brunyé et al., 2010). Second, identifying and comparing route options and choosing the most viable path (the second and third phases in route planning: Brunyé et al., 2010) often requires taking into account transits between different lines or even transportation modes and these transits often have substantial impact on travel time or convenience (Ettema, Friman, Gärling, Olsson & Fujii, 2012; Raveau, Guo, Munoz, & Wilson, 2014). This is further complicated by the fact that network transportation maps usually do not preserve metric relationships between stations and do not contain information about the frequency with which lines operate (Guo, 2011). It may therefore be faster to choose a longer route if that route has fewer transfers than the alternatives which require more transfers (Chowdhury & Ceder, 2013; Friman, 2010; Hine & Scott, 2000).

2. Motivation

While planning routes using an unknown network map is a common and complex task, our understanding of the underlying cognitive and visual processes is limited. In the present study we present a route-planning paradigm in which we use eye-tracking to investigate some of the underlying processes. Specifically, we explore and report behavioural and eye-tracking markers for the different phases involved in route planning from maps: first, finding the origin and destination and their spatial relation (hereafter '*Search Phase*'), and second, identifying, comparing, and selecting a viable route option (hereafter '*Planning and Selection Phase*'). In the experiment we manipulated the number of transfers required to get from start to destination, which we predicted would impact on behaviour in the Planning and Selection Phase, but should have little impact on the Search Phase. In our analysis of gaze behaviour, we consider established measures such as dwelling time in the centre vs. the periphery of maps (Brunyé and Taylor, 2009) and pupil size as a measure of cognitive load in spatial processing (de Condappa & Wiener, 2016). In addition, we explored novel measures by relating gaze behaviour to various parameters of the maps or stations, such as the number of lines that go through a station. We hypothesized that stations that allow for transfers were particularly important and therefore attended to during the Planning and Selection Phase but less so during the Search Phase.

3. Method

3.1. Participants

Twenty participants (10 women, mean age 26.1 years, SD = 5.7) took part in the study. They were mostly university students from Bournemouth University (UK) and paid 8 pounds an hour.

3.2. Material

3.2.1. Maps

We created 13 fictitious maps (12 for the experiment and one for practice, see Figure 1 for an example), which are similar to existing transport network maps (bus or underground maps). To control for the visual complexity of different maps, each map featured the same number of stations (17 white rectangles with the station name in black font [Calibri, 18pts]) and the same number of links between stations (22 links). Different link colours and styles (e.g., dotted, filled, and double) indicated different lines. The number of links per line varied from three to six and the number of lines on map varied between five (10 maps) and six (3 maps).

Stations were subdivided into peripheral stations (i.e., there were no stations left or right and/or above and/or below) and central stations (i.e., there were stations left, right, above and below) and into passing stations (no transfer possible) and transfer stations either with one, two or three possible transfers. For each map the number of peripheral stations varied from 9 to 11 and the number of central stations varied from 6 to 8. The number of passing stations varied from 7 to 10, the number of stations with one transfer varied from 3 to 9, the number of stations with 2 transfers varied from 1 to 4 and only one station on one map has 3 transfers.

3.2.2. Routes

Five different origin-destination pairs were chosen for each of the 12 maps, summing up to a total of 60 planning tasks with a unique origin and destination pair for each trial. Twenty planning tasks did not require a transfer, 20 required at least one transfer and 20 required at least two transfers. We selected the planning tasks (i.e., the origin – destination pairs) such that there always was at least one alternative solution (route; Mean = 1.62 routes; SD = 0.76) that required one additional transfer as compared to the solution with the minimal number of transfers. The complexity of a planning task is defined by the minimum number of transfers required, which was zero, one or two.

[Insert here Figure 1]

Half of the routes did not feature an alternative that required the same number of transfers (18 in the ‘no transfer’ condition; 9 in the ‘one transfers’ condition; and 3 in the ‘two transfers’ condition). 19 routes had one alternative that had the same number of transfer (1 in the no transfer condition; 10 in the one transfer; and 8 in the two transfers). Finally, 11 routes had two alternatives with the same number of transfer (1 in the ‘no transfer’ condition; 1 in the ‘one transfer’ condition; and 9 in the ‘two transfers’ condition).

The average route length (i.e. the number of stations along the route including origin and destination) was 4.95 stations (SD = 1.17). The average route length for the no transfer condition was 4.40 (SD = 0.25), it was 5.15 (SD = 0.25) for the one transfer condition, and 5.30 (SD = 0.25) for the two transfers condition.

On average, 35.6% (SD = 23.2) of the route is peripheral (i.e. the percentage of stations of the specific routes that were located in the peripheral part of the map. This was similar for route of different complexity (34.7% (SD = 5.3) for the ‘no transfer’ condition, 34.9% (SD = 5.3) for the ‘one transfer’ condition, and 37.3% (SD = 5.3) for the ‘two transfer’ condition).

3.2.3. Apparatus

The maps were displayed on a 20” CRT screen at a resolution of 1024 × 768 pixels and a refresh rate of 120 Hz. Participants sat in front of the monitor at a distance of 60 cm, such that the resulting visual angle of the stimuli displayed was 37° (horizontally) × 28° (vertically). Eye movements were recorded using a SR Research Ltd. Eyelink 1000 eye-tracker, sampling pupil position at 500 Hz. Head movements were constrained using a chin rest. The eye-tracker was calibrated using a 9-point grid. The fixations were defined using the detection algorithm supplied by SR Research.

3.3. Procedure

Participants were tested individually in a quiet room. The total duration of the experiment was roughly 40 minutes. Participants first signed the consent form and were then instructed that they would be given different planning problems and that their task was to find the route with the minimum number of transfers between the origin and the destination. They were also informed that they will have to solve five planning tasks with the same map, before they would be presented with a novel map.

3.3.1. Training phase

The training phase was composed of 5 planning tasks presented on one map. Each trial began with the presentation of the names of the origin and the destination on the screen. These were displayed at the centre of the screen, the origin above the destination. Participants were instructed to read and memorise the names of origin and destination and to press any button on the response box to proceed. After a drift correction, which required participants to look at a fixation cross in the centre of the screen, the actual map was presented. Participants then had to report the minimal number of transfers for each planning task by pressing the corresponding buttons of the response box which were labelled "0" (for no transfers required), "1" (for one transfer), "2" (for two transfers) or "3" (for three transfers). Participants were given feedback about their performance during the training phase.

3.3.2. Test phase

Once the participants understood the procedure and completed all five training trials, they entered the test phase. The procedure of each single trial in the test phase was identical to the training phase apart from the fact that participants did not receive feedback. **The participants were presented with 12 maps and five trials per map, for a total of 60 trials. The order of the 12 maps as well as the order in which the five trials for each map were presented was randomized.**

4. Data collection and analyses

4.1. Trial phases

We subdivided each trial into two phases on the basis of our gaze behaviour analysis. The Search Phase is the initial part of the trial during which participants search for the origin and the destination station. The Search Phase was defined as the part of the trial until participants had gazed at both the origin and destination station, for the first time. The Planning and Selection Phase is the latter part of the trial after the Search Phase was completed. It includes the search of path alternatives and the selection between them.

We only failed to split 34 out of the 1200 trials into two phases. In these trials participants did not look at the origin and/or destination stations. The average search time and the average number of fixations, as well as standard deviations, and

coefficients of variation are presented in Table 1. The analyses were done by items (route task), participants, and maps.

On average, participants made 19.8 fixations before having gazed at both the origin and destination. The variation in this measure is similar when analyzed by items, participants, but smaller when analyzed by maps (see Table 1).

Table 1. This table presents the averages, standard deviations, and coefficients of variation for search time, and number of fixations. The analyses are done by items (route task), participants, and maps.

		N	Mean	SD	Coefficient of variation
Items	Time	60	4444	762.8	17.2
	Number of Fixations	60	19.7	3.2	16
Participants	Time	20	4471	729.7	16.3
	Number of Fixations	20	19.8	3.1	15.5
Maps	Time	12	4446	293.9	6.6
	Number of Fixations	12	19.7	1.3	6.5

On average, participants made only 2.02 (*SD* = 1.38) fixations outside of the interest areas during the Search Phase, and 6.4 (*SD* = 2.34) during the Planning and Selection Phase.

4.2. Performance data

The participant's responses (0, 1, 2 or 3) for each trial as well as their response times were recorded. We also measured the amount of time spent in each of the two phases defined above.

4.3. Eye movement data

4.3.1. Interest area

To analyse the eye-movement data we created 17 interest areas for each map covering the 17 stations. **The interest areas were rectangular and only marginally larger than the stations' rectangles.**

4.3.2. Recorded measures

We recorded the fixation number, time and location (i.e., interest area) as well as the saccade amplitude in visual degrees (i.e., average distance between fixations) and pupil size (area in pixels). All these measures were calculated for the both trial phases.

Fixations shorter than 80 milliseconds were removed from the data set. Fixations were detected using SR Research's velocity and acceleration based algorithm with a fixed velocity threshold of 30°/s and an acceleration threshold of 8000°/s (Eyelink User Manual, 2005).

As the number of fixations and the time to perform the phases were highly correlated for the both phases (Search phase: $r = 0.94$, $p < 0.001$; Planning and Selection phase: $r = 0.95$, $p < 0.001$), we only retained the time for the analysis.

4.4. Gaze behaviour indicators

Based on the recorded measures, we then calculated the following gaze behaviour indicators:

- ***Ratio of time spent looking at central stations during the Search Phase:*** This value describes the time participants spent looking at central stations as compared to the time they spent looking at any station during the Search Phase. This value describes whether participants had a preference to look at central stations in the Search Phase. For each map and each trial, we first summed up the time participants spent looking at central stations in the Search Phase. As different maps had different numbers of central stations this value was normalised by dividing it by the number of central stations (value 1). We then calculated the overall time participants gazed at peripheral and central stations and divided this value by the number of stations (value 2). Value 2 describes the average time participant spend looking at any station (independent of whether it was a peripheral or central station). Finally we divide value 1 by value 2 to calculate the ratio between the time spend looking at central stations compared to any station. If the resulting value was exactly 1, it means that the participants spent the same amount of time inspecting central stations as compared to any other station. If the value was greater than 1, they spend more time inspecting central stations and if it was smaller than 1, they spend less time inspecting the central stations.

We used the same kind of calculation to obtain the following variables:

- ***Ratio of time spent looking at peripheral stations during the Search Phase;***
- ***Ratio of time spent looking at stations that feature one line, two lines or three lines during the Search Phase/ Planning and Selection phase;***
- ***Ratio of time spent looking at origin/destination stations during the Planning and Selection Phase.***

For all indicators, we only considered fixations that were directed to one of the interest areas.

5. Hypotheses

The main aim of this study was to develop a better understanding of how the process of planning routes from transportation network maps is reflected in behaviour in general and gaze behaviour in particular. We predict that:

- Accuracy should decrease with increasing task complexity.
- The length of the Search Phase (Origin-destination search time) should be independent of task complexity, while the length of Planning and Selection Phase (planning and selection time) should increase with increasing task complexity.
- The saccade amplitude during the Search Phase should be larger than during the Planning and Selection Phase. This is, because in the latter phase, participants will be primarily tracing lines, and more saccades will be made between connected and therefore neighbouring stations than in the Search Phase.
- **Pupil size is a reliable measure of cognitive load (Beatty, 1982). Given the additional cognitive load when planning a route as compared to searching for start and destination, we expect larger pupil size in the Planning and Selection Phase than in the Search Phase. Moreover, we expect to observe an effect of task complexity on the pupil diameter during the Planning and Selection Phase, but not during the Search Phase.**
- **During the Search Phase, the ratio of time spend looking at central stations should be higher than the ratio of time spend looking at peripheral stations because of the observed bias towards the centre of the map (Brunyé & Taylor, 2009). Moreover, stations allowing for transfers are mostly in the centre of the**

transportation network maps. We therefore expected that participants spend more time looking at the central rather than the peripheral part of the map during the Planning and Selection phase, and that this preference should be larger than during the Search Phase. We also expected that with increasing route complexity requiring more transfers, participants should focus more on the central part of the map during the Planning and Selection phase.

- The ratio of time spent looking at origin and destination stations should decrease with increasing route complexity because of the higher number of connecting stations that have to be found.
- Similarly, the ratio of time spend looking at connecting stations, i.e., stations with more than one line, should increase in the Planning and Selection Phase as compared to the Search Phase. Furthermore, this increase should be stronger for more complex planning tasks.

6. Results

We used analysis of variance (ANOVA) to analyse our results for performance and eye movement data. The post-hoc analyses were systematically done with the Bonferroni test. To control for possible confounds between the task complexity, route length, and the number of alternatives, we also analyse our data by items (planning task) using ANCOVA with route length, and the number of alternatives as covariates.

6.1. Analyse of potential confounds

To analyse potential confounds between the task complexity of the route, the route length, the number of alternatives, and the percentage of the route in the peripheral part of the map, we analysed their correlations. We observed a positive and significant correlation between the task complexity and the number of alternatives (r = 0.61, p < 0.001). We also observed a positive and significant correlation between the task complexity and the route length (r = 0.32, p = 0.014). The correlation between the task complexity and the percentage of the route in the peripheral part of the map was not significant (r = 0.05, p = 0.73).

A one way ANOVA with the factor task complexity (0, 1, 2) on the number of alternative revealed a significant effect ($F(2, 57) = 17.76$, $p < 0.001$, $\eta_p^2 = 0.38$). We

observed that more complex routes featured more alternative solutions. Post-hoc tests showed significant differences between the no transfer and the two transfers condition (*p* < 0.001) and between the one transfer and two transfer condition (*p* < 0.001).

A one way ANOVA with the factor task complexity (0, 1, 2) on route length showed a significant effect ($F(2, 57) = 3.7$, $p = 0.03$, $\eta_p^2 = 0.12$), highlighting that more complex routes are longer. Post-hoc analysis revealed a significant difference only between the no transfer and two transfer condition ($p = 0.04$).

6.2. Performance data

6.2.1. Accuracy

Overall performance was very good. In 81% of the cases, participants correctly reported the minimal number of transfers required to get from the origin to the destination.

As participants made five consecutive trials on the same map, we took this factor (i.e., repetition) into consideration. A 3 x 5 ANOVA with the within factors task complexity (i.e., number of transfer, 0, 1, 2) and number of repetitions (1, 2, 3, 4, 5) revealed significant main effects of task complexity ($F(2, 38) = 6.76$, $p < 0.005$, $\eta_p^2 = 0.26$) and repetition ($F(4, 76) = 3.6$, $p = 0.009$, $\eta_p^2 = 0.16$). The interaction was also significant ($F(8,152) = 4.31$, $p < 0.001$, $\eta_p^2 = 0.18$).

Surprisingly, participants' performance was lower in the no transfer condition (74%) than in the conditions with one transfer (85%; post hoc test: $p = 0.004$) or two transfers (83%; post hoc test: $p = 0.027$, see Figure 2).

Post hoc tests revealed a significant difference only between the first and the second trial with the same map ($p = 0.004$). The interaction between the repetition and the task complexity did not render any clear effects.

[Insert here Figure 2]

The 3 (task complexity) x 5 (repetition) ANCOVA with route length, and the number of alternatives as covariates did not render an effect of route length (F<1), task complexity ($F(2, 43) = 1.14$, $p = 0.3$), number of alternatives ($F(1, 43) = 3.37$, $p = 0.07$), or repetition (F<1). The interaction between task complexity x repetition was not

significant (F(8, 43) = 1.48, p = 0.19). This analysis shows that, when considering route length factor and the number of alternative, the effect of the task complexity and of the repetition factors did not influence the accuracy.

6.2.2. The effect of phase, number of transfers and repetitions on the time to complete the task

As described above, we used the eye-tracking data to split trials into the Search Phase and the Planning and Selection Phase. Here we analyse the time needed to perform these two phases. The analysis is restricted to correct trials only.

In order to verify our hypothesis concerning the time spent on searching origin and destination and planning routes between them, we ran a 2 x 3 x 5 ANOVA with the within factors phase (Search Phase, Planning and Selection Phase), task complexity (0, 1, 2), and repetition (1, 2, 3, 4, 5) on time. The analysis revealed significant main effects of phase (F(1, 19) = 65.9, p < 0.001, η_p^2 = 0.78) and task complexity (F(2, 38) = 94.38, p < 0.001, η_p^2 = 0.83), but no main effect of repetition (F(4, 76) = 2.31, p = 0.07). All two way interactions were significant: task complexity x phase (F(2, 38) = 65.9, p < 0.001, η_p^2 = 0.78), task complexity x repetition, (F(8,152) = 3.6, p = 0.008, η_p^2 = 0.16) and repetition x phase (F(4,76) = 3.7, p = 0.008, η_p^2 = 0.16). The three way interaction was also significant (F(8,152) = 3.35, p = 0.001, η_p^2 = 0,15).

The post-hoc analysis on task complexity showed significant effects across all complexities (all p < 0.001), highlighting that more complex planning tasks (i.e. with more transfers) require more time to solve.

Post-hoc analysis on the phase x task complexity interaction did not reveal any difference in time between different levels of task complexity in the Search Phase (all p > 0.05). In the Planning and Selection Phase, in contrast, we observed an increase in time with increasing complexity. The differences in time between all levels of task complexity were significant (all p < 0.001, see Figure 3). These results are in line with our predictions, i.e., that search time should not be affected by the number of transfers required (task complexity), while the planning and selection time should increases with increasing task complexity. This pattern also strongly suggests that gaze behaviour can be used to split the planning process into a Search Phase and a Planning and Selection Phase.

[Insert here Figure 3]

Post hoc analysis on the task complexity x repetition interaction revealed a constant increase of the time with increasing task complexity for the repetitions 1, 3, and 5 (all $p < 0.01$). However, for the repetitions 2, and 4 we did not observe a significant difference in time between the routes with no transfer, and one transfer ($p > 0.05$). The analysis on the phase x repetition interaction did not reveal the influence of the repetition on the effect of phase clearly: however, the Search Phase was shorter than the Planning and Selection Phase for all repetition levels (all $p < 0.001$).

To analyse the three way interaction we ran independent task complexity x phase ANOVAs for each repetition (1, 2, 3, 4, and 5). The task complexity x phase interaction was significant for each repetition (repetition 1: $F(2, 38) = 53.55$, $p < 0.001$, $\eta_p^2 = 0.74$; repetition 2: $F(2, 38) = 45.52$, $p < 0.001$, $\eta_p^2 = 0.71$; repetition 3: $F(2, 38) = 25.31$, $p < 0.001$, $\eta_p^2 = 0.57$; repetition 4: $F(2, 38) = 27.86$, $p < 0.001$, $\eta_p^2 = 0.59$; and repetition 5: $F(2, 38) = 28.06$, $p < 0.001$, $\eta_p^2 = 0.60$), and the observed pattern was the same for all the repetitions (see Figure 4).

[Insert here Figure 4]

The analysis by items revealed effects of task complexity ($F(2, 43) = 63.43$, $p < 0.001$, $\eta_p^2 = 0.75$) and of phase ($F(1, 43) = 6.35$, $p = 0.02$, $\eta_p^2 = 0.13$), but no effects of route length ($F<1$), number of alternatives ($F<1$) and of repetition ($F(4, 43) = 1.03$, $p = 0.4$). Only the task complexity x phase interaction was significant ($F(2, 43) = 49.3$, $p < 0.001$, $\eta_p^2 = 0.69$). The other interactions were not significant: task complexity x repetition ($F(8, 43) = 1.61$, $p = 0.15$), phase x route length ($F(1,43) = 1.02$, p = 0.32), phase x number of alternatives ($F<1$), phase x repetition ($F(4, 43) = 1. 8$, $p = 0.15$), and task complexity x phase x repetition ($F(8, 43) = 2$, $p = 0.068$).

The post hoc analysis of the task complexity x phase interaction showed that time increased with increasing task complexity during the Planning and Selection Phase (all $p < 0.001$), but not during the Search Phase (all $p > 0.05$).

The analysis by items taking into consideration route length confirms the results obtained previously.

Repeated exposure to the same maps did not render clear effects in either the accuracy or time analysis, and was therefore excluded from the following analyses.

6.3. Eye movement data

6.3.1. Saccade Amplitude

To test if saccade amplitude is influenced by the task complexity and the trial phase, we ran an ANOVA with the within factor task complexity (0, 1, 2) and phase (Search Phase, Planning and Selection Phase) on saccade amplitude. The analysis revealed significant main effects of task complexity ($F(2,38) = 16.87$, $p < 0.001$, $\eta_p^2 = 0.47$) and phase ($F(1, 19) = 96.18$, $p < 0.001$, $\eta_p^2 = 0.84$) as well as a significant interaction ($F(2, 38) = 30.54$, $p < 0.001$, $\eta_p^2 = 0.62$).

In line with our hypothesis, saccade amplitudes were smaller in the Planning and Selection Phase than in the Search Phase, and this difference was bigger for the two transfers' condition than for the other conditions (see Figure 4). We found that saccade amplitude in the Search Phase was not influenced by task complexity (post hoc test, all $p > 0.05$). In contrast, saccade amplitude decreased in the two transfers' condition compared to the zero and one transfer conditions in the Planning and Selection phase (no transfer vs. two transfers, $p < 0.001$; one transfers vs two transfers, $p < 0.001$).

[Insert here Figure 5]

The analysis by items revealed significant main effects of route length ($F(1,55) = 4.03$, $p = 0.049$, $\eta_p^2 = 0.07$), task complexity ($F(2,55) = 3.15$, $p = 0.05$, $\eta_p^2 = 0.10$) and phase ($F(1,55) = 20.93$, $p < 0.001$, $\eta_p^2 = 0.28$). We did not observe a significant effect for the number of alternatives ($F<1$). The interactions phase x route length ($F(1,55) = 4.82$, $p = 0.03$, $\eta_p^2 = 0.08$) and phase x task complexity ($F(2,55) = 7.59$, $p = 0.001$, $\eta_p^2 = 0.22$) were significant while the phase x number of alternatives interaction was not significant ($F<1$).

Taking into account route length, and the number of alternatives did not change the pattern of results. Saccades amplitude was still larger in the Search Phase than in the Planning and Selection Phase. We also observed a decrease of the saccade amplitude for the two transfers' condition that was due to a major decrease of saccade amplitude in the Planning and Selection Phase ($p = 0.004$) for the routes with two transfers.

6.3.2. Pupil size

In order to test the hypothesis that the Planning and Selection Phase poses a higher cognitive load than the Search Phase, we ran an ANOVA with the within factors phase (Search Phase, Planning and Selection Phase) and task complexity (0, 1, 2) on pupil size. The analysis revealed a main effect of the phase ($F(1, 19) = 60$, $p < 0.001$, $\eta_p^2 = 0.76$) demonstrating larger pupil size in the Planning and Selection Phase (1373 px) in during the Search Phase (1259 px). The effect of task complexity did not reach significance ($F(2, 38) = 3.21$, $p = 0.052$) and the interaction was not significant ($F(2, 38) = 1.63$, $p = 0.21$).

The analysis by items confirmed the significant effect of the phase ($F(1, 55) = 51.83$, $p < 0.001$, $\eta_p^2 = 0.49$). We did not observe significant effects of task complexity ($F<1$), number of alternatives ($F(1, 55) = 2.75$, $p = 0.1$) or route length ($F(1, 55) = 3.64$, $p = 0.06$). None of the interactions were significant: phase x number of alternatives ($F(1, 55) = 2$, $p = 0.16$), phase x route length ($F<1$), and phase x task complexity ($F(2, 55) = 2.13$, $p = 0.13$).

6.3.3. Gaze distribution between central and peripheral stations

To test our hypotheses concerning the distribution of gaze between the central and peripheral part of the map, we ran an ANOVA with the within factors task complexity (0, 1, 2), phase (Search Phase, Planning and Selection Phase), and location of station (central, peripheral) on the ratio of time spend looking at stations. The analysis revealed significant main effects of location of station ($F(1, 19) = 1233.7$, $p < 0.001$, $\eta_p^2 = 0.98$), the task complexity ($F(2, 38) = 4.3$, $p = 0.02$, $\eta_p^2 = 0.19$), and of phase ($F(1, 19) = 296$, $p < 0.001$, $\eta_p^2 = 0.94$). The phase x location interaction was significant ($F(1, 19) = 278.6$, $p < 0.001$, $\eta_p^2 = 0.94$) as was the three way interaction ($F(2, 38) = 12.2$, $p < 0.001$, $\eta_p^2 = 0.39$). The task complexity x location interaction was not significant ($F(2, 38) = 2.9$, $p = 0.06$).

Post hoc results showed that the central part of the map was always attended to more than the peripheral part (all p < 0.001), but the difference between the central and peripheral stations is larger during the Planning and Selection phase than during the Search Phase (see Figure 6).

[Insert here Figure 6]

To analyse the three way interaction we ran independent phase x location ANOVAs for each level of task complexity. Results showed that the interaction between the phase and the location was significant for all three levels of task complexity: no transfer (F(1, 19) = 69.8, p < 0.001, η_p^2 = 0.76), one transfer (F(1, 19) = 196.4, p < 0.001, η_p^2 = 0.91), and two transfers (F(1, 19) = 245, p < 0.001, η_p^2 = 0.93). As show on the Figure 7, the difference in gaze distribution between the central and peripheral part during the Planning and Selection phase increased with task complexity.

Overall these results confirmed our hypothesis that central stations are attended more than peripheral stations, that this difference was larger during the Planning and Selection phase than during the Search Phase, and that it increased with increasing task complexity.

[Insert here Figure 7]

The analysis by items confirmed the effects of location (F(1, 55) = 18.8, p < 0.001, η_p^2 = 0.25), and phase (F(1, 55) = 4.4, p = 0.04, η_p^2 = 0.07). The interaction between the location and the phase was also significant (F(1, 55) = 10.08, p = 0.002, η_p^2 = 0.15). We did not observe effects of the route length (F<1), number of alternatives (F<1), and task complexity (F<1). None of the interactions were significant. These results confirmed that participants spend more time looking at central than peripheral station during both phases, and that this effect is stronger during the Planning and Selection phase than during the Search Phase.

6.3.4. Gaze distribution between origin and destination stations during Planning and Selection phase

To test our hypothesis that the time spent looking at origin and destination stations should decrease with increasing route complexity, we ran an ANOVA with the within factors task complexity (0, 1, 2) and stations (origin, destination) on the ratio of time spent looking at origin and destination stations during Planning and Selection phase. This analysis revealed significant main effects of task complexity (F(2, 38) = 405.2; p < 0.001, η_p^2 = 0.96) and type of station (F(1, 19) = 55.9, p < 0.001, η_p^2 = 0.75) as well as a significant interaction (F(2,38)= 6.8; p = 0.003, η_p^2= 0.26, see Figure 8).

[Insert here Figure 8]

The post-hoc analysis on the interaction shows significant differences between origin and destination stations for the no and the one transfer condition (both $p < 0.005$), but no difference for the two transfers condition ($p = 0.21$). Finally, post-hoc analysis on the task complexity factor revealed that the ratio of time spent looking at origin and destination station decreases with increasing task complexity (all $p < 0.001$). This supports our hypothesis that the time spent looking at the origin and the destination stations during the Planning and Selection phase decreased with increasing task complexity as participants spend more time planning the route between these two locations.

These results are confirmed by the analysis by items that showed effects of route length ($F(1, 55) = 7.84$, $p = 0.007$, $\eta_p^2 = 0.12$) and task complexity ($F(2, 55) = 61.65$ $p < 0.001$, $\eta_p^2 = 0.69$). We did not observe significant effects of the number of alternatives ($F<1$) and the type of station ($F(1, 55) = 1.33$, $p = 0.25$). None of the interactions were significant (all $F<1$).

6.3.5. Gaze distribution between stations according to their number of lines

To verify the hypothesis that participants spend more time looking at transfer stations (i.e., stations with several lines) when planning more complex routes, we ran an ANOVA with the within factors number of lines (1, 2, 3), task complexity (0, 1, 2) and phase (Search Phase, Planning and Selection Phase) on the ratio of time spend looking at stations with differing numbers of lines. The analysis revealed significant main effects of the number of lines ($F(2,38) = 425.43$; $p < 0.001$, $\eta_p^2 = 0.96$), task complexity ($F(2, 38) = 93.19$, $p < 0.001$, $\eta_p^2 = 0.83$), and phase ($F(1, 19) = 267.51$; $p < 0.001$, $\eta_p^2 = 0.93$). All interactions were significant: number of lines x task complexity ($F(4, 76) = 79.3$; $p < 0.001$, $\eta_p^2 = 0.81$), number of lines x phase ($F(2,38) = 261.4$, $p < 0.001$, $\eta_p^2 = 0.93$), task complexity x phase ($F(2, 38) = 8.51$, $p < 0.001$, $\eta_p^2 = 0.31$), and number of lines x task complexity x phase ($F(4,76) = 4.9$, $p < 0.001$, $\eta_p^2 = 0.20$).

Overall, the time participants attend to stations increases with the number of lines these stations feature (all $p <0.001$). Participants also spend more time attending to transfer stations in the Planning and Selection Phase than in the Search ($p < 0.001$). This difference between phases was particularly strong for stations with three lines ($p < 0.001$, see Figure 9), while it was not significant for stations with two lines ($p > 0.5$). These results are in line with our hypothesis stating that stations with a high number of lines are more important to attend to in the Planning and Selection Phase as compared to the Search Phase.

[Insert here Figure 9]

Post-hoc analysis on the task complexity x number of lines interaction (see Figure 10) revealed an effect of task complexity on the ratio of time spent looking at stations with three lines (all $p < 0.001$), but no effect on stations with one or two lines (all $p > 0.05$). This result contradicts our hypothesis that transfer stations featuring a larger number of lines are particularly important for planning tasks that require several transfers.

[Insert here Figure 10]

To analyse the three way interaction, we ran independent phase x number of lines ANOVAs for each level of task complexity. The phase x number of lines interaction was significant for all task complexities (no transfer: $F(2, 38) = 86.75$; $p < 0.001$, $\eta_p^2 = 0.82$; one transfer: $F(2, 38) = 161.75$; $p < 0.001$, $\eta_p^2 = 0.89$; and two transfers: $F(2, 38) = 115.73$; $p < 0.001$, $\eta_p^2 = 0.86$), and the pattern of result is the same for all task complexities.

For the analysis by items we removed trials for one map, because it featured no transfer stations with three lines. The analysis by items did not revealed any significant effects.

7. Discussion

The main objective of this study was to develop a better understanding of how people plan routes using public transport network map. More specifically we were interested in how people visually explore transportation network maps during two phases of route planning: the initial search for origin and destination and the planning and selection of the best route. To do so we gave participants origin-destinations pairs and asked them to find the route with the minimum number of transfers between them using fictitious transport network maps. We report different behavioural makers, including gaze behaviour, for the two phases.

We found that accuracy for the simplest routes, i.e., the routes that did not require a transfer, was lower than for routes that required one or two transfers. While this result seems surprising at first glance, it can be explained by the fact that numerous routes without transfer required substantial detours, i.e., shorter routes with one or two transfers were available, and it is possible that this misled participants. **As performance for more complex routes was, in fact, better than for simple routes, we do not believe that participants have misunderstood the task itself or confused transfer with pass-through stations. Moreover, the analysis by items did not reveal a significant effect of task complexity.**

We used the eye-tracking data to split each trial into two phases: the Search Phase and the Planning and Selection Phases and we predicted that search time should be independent of the task complexity of the planning task. Indeed, we found that search time was not affected by the task difficulty while the planning and selection time increased with the increasing task complexity. This result suggests that with the increasing task complexity more processes, such as finding transfer stations and comparing routes, are needed, while these are not required during the Search Phase. Furthermore, results show that saccades during the Search Phase were longer than during the Planning and Selection Phase. We also observed an effect of task complexity on saccades amplitude during the Planning and Selection Phase, with a decrease of amplitude for the planning tasks that required two transfers. **Moreover, we observed an increase in pupil size during the Planning and Selection Phase, suggesting an increase in cognitive load when moving from the Search Phase to the Planning and Selection Phase.** These results are in line with the idea that a global map exploration is performed during the Search Phase and that the connections between stations is not relevant in this initial phase. During the Planning and Selection Phase, in contrast, a more precise exploration is required and connections between neighbouring stations become relevant. Processes required during the Planning and Selection Phase, such as encoding the exact locations of connecting stations or routes in short term memory and manipulating this information, is also more cognitively demanding than a pure visual search (Gärling et al., 1986, Wiener, Ehbauer & Mallot, 2009). Such increases in cognitive demands are also known to result in shorter saccades (Just & Carpenter, 1976; Pomplun et al., 2001).

Overall, the results are in line with the proposition that route planning involves different sequential phases (Benshoof, 1970; Bovy & Stern, 1990; Brunyé et al., 2010; Gärling et al., 1983; Golledge, 1995). Specifically, our results suggest that there are, at least, two clearly distinct phases in route planning from maps which involve different cognitive processes and result in systematic differences in gaze behaviour.

We proposed that the Search Phase, i.e. the initial search for the origin and destination locations, is similar to a visual exploration with two targets. Literature on map exploration has previously shown a bias towards the centre of the map at early exploration (Brunyé & Taylor, 2009). Our results are consistent with these previous findings, confirming that participants have a bias towards attending central stations during the Search Phase..

According to literature the second and third stages of route planning, that we have grouped into the Planning and Selection Phase,, involve finding and comparing routes and then selecting one of them (Benshoof, 1970; Bovy & Stern, 1990; Brunyé et al., 2010; Gärling et al., 1983; Golledge, 1995). We predicted that with increasing numbers of transfers required, i.e., with increasing route task complexity, participants will have to focus more on connection stations rather than at the origin and destination in order to plan and compare routes alternatives. Our results confirmed this hypothesis. This is also in line with the results that demonstrate that participants tend to spend more time gazing at stations with only one line in the Search phase as compared to the Planning and Selection Phase. For stations with three lines the opposite is true: participants spend more time attending to such transfer stations with three lines in the Planning and Selection phase than in the Search Phase. **Finally, participants spend more time spent looking at central than peripheral stations in the Planning and Selection phase and, this effect increases with increasing task complexity. These results can be explained by the fact that stations allowing for transfers are typically in the central part of transportation maps, and as participants have to look for stations were transfers are possible, they tend to focus their attention to the central part of the map.**

Two of our results were not expected. First, we hypothesised that the increasing task complexity of the planning task would result in a preference to attend to stations with a higher number of lines, as these stations are crucial for transfers to other lines. Our results, however, showed the opposite effect. One explanation for this is that the maps we used introduced a bias. As discussed above, participants spent more time looking at origin and destination stations when planning routes that do not require a transfer than when planning more complex routes. However, most of the origin and destination stations in the no transfer tasks were connecting stations, i.e., they had two lines (51.3%) or three lines (28.2%), whereas the majority of origin or destination stations in the transfer tasks only had one line (82.5%). This imbalance could explain why stations with a higher number of lines were less attended to when planning route with two transfers as compared to routes that required less transfers.

Second, we observed that destination stations received more attention than origin stations. One explanation for this result can be found in literature on route planning strategies. One prominent planning strategy is the *Direction-based strategy* (Conroy Dalton, 2003; Golledge, 1995; Hölscher, Tenbrink & Wiener, 2011). When people follow this strategy during navigation, they tend to remain oriented in direction of the destination as much as possible. Previous studies have shown that this strategy leads to route choices that minimise the changes of direction. Note that this strategy requires the navigator to know the location of the destination station well, which may lead to frequent checks of the destination location during planning which could explain why destination stations receive more attention than origin stations. While further investigations are needed to validate this explanation, it highlights that eye-tracking data is a promising tool to develop a better understanding of the strategies used during route planning from map.

In summary, we have presented a number of novel findings, including data from eye-tracking, that support the notion that route planning is subdivided into different phases (Benshoof, 1970; Bovy & Stern, 1990; Brunyé et al., 2010; Gärling et al., 1983; Golledge, 1995). Our research studies, to our knowledge for the first time, how people visually explore transportation maps when planning routes. Our main findings demonstrate that there are differences between two phases of the route planning process, i.e., the search of origin and destination location and the planning and selection of one route, which is supported by different behavioural markers. In fact, the early exploration of the map, during the search of origin and destination stations location, is oriented toward the centre of the map. We also highlight that, once these stations are located, the map exploration changes, it become more meticulous (saccades amplitude) and oriented towards transfer stations. Our results demonstrate experimentally that different cognitive and visual processes are involved during the Search Phase and Planning and Selection Phase of route planning. Our finding are, however, not completely coherent with the proposed three phases of route planning at theoretical level (Brunyé et al., 2010; Golledge, 1995). It may, at this point be important to reassess the second phase (search of routes and comparison) and third phase (selection of one route) of the proposed three stage model. Let’s assume a case where multiple route option exists (note that in transportation network maps there are vast numbers of route options between any two locations). Is it reasonable to assume that planners first search all possible routes before selecting one? We propose that the second and third stage (route search stage and selection stage) are tightly interlinked and interactive, such that unsuitable route alternatives can be eliminated while the search and comparison process is still ongoing.

Compliance with Ethical Standards

Ethical approval: Ethical approval for the study was granted by the Bournemouth University committee. All procedures performed in this study were in accordance with 1964 Helsinki declaration and its later amendments as well as comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Disclosure of potential conflicts of interest: The authors declare that there were no conflicts of interest.

Bibliography

Bailenson, J. N., Shum, M. S., & Uttal, D. H. (1998). Road climbing: Principles governing asymmetric route choices on maps. *Journal of Environmental Psychology, 18*(3), 251–264. doi:10.1006/jevp.1998.0095

Bailenson, J. N., Shum, M. S., & Uttal, D. H. (2000). The initial segment strategy: A heuristic for route selection. *Memory and Cognition, 28*(2), 306–318. doi:10.3758/BF03213808

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychological Bulletin, 91(2), 276–292.

Beck, M. R., Trenchard, M., van Lamsweerde, A., Goldstein, R. R., & Lohrenz, M. (2012). Searching in clutter: Visual attention strategies of expert pilots. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 56*, 1411–1415. doi:10.1177/1071181312561400

Benshoof, J. A. (1970). Characteristics of drivers' route selection behavior. *Traffic Engineering & Control*, 11, 604-606.

Bovy, P. H. L., & Stern, E. (1990). Route choice: Wayfinding in transport networks. *Transportation Research Part A: Policy & Practice*,27, 338-339. doi:10.1007/978-94-009-033-4

Brunyé, T. T., Andonova, E., Meneghetti, C., Noordzij, M. L., Pazzaglia, F., Wienemann, R., Mahoney, C. R., & Taylor, H. A. (2012). Planning routes around the world: International evidence for southern route preferences. *Journal of Environmental Psychology, 32*(4), 297–304. doi:10.1016/j.jenvp.2012.05.003

Brunyé, T. T., Gagnon, S. A., Waller, D., Hodgson, E., Tower-Richardi, S., & Taylor, H. A. (2012). Up north and down south: Implicit associations between topography and cardinal direction. *The Quarterly Journal of Experimental Psychology, 65*(10), 1880–1894. doi:10.1080/17470218.2012.663393

Brunyé, T. T., Mahoney, C. R., Gardony, A. L., & Taylor, H. A. (2010). North is up(hill): Route planning heuristics in real-world environments. *Memory and Cognition, 38*(6), 700–712. doi:10.3758/MC.38.6.700

Brunyé, T. T., & Taylor, H. A. (2009). When goals constrain: Eye movements and memory for goal-oriented map study. *Applied Cognitive Psychology*, *23*(6), 772–787. doi:10.1002/acp.1508

Casakin, H., Barkowsky, T., Klippel, A., & Freksa, C. (2000). Schematic maps as way finding aids. In C. Freksa, C. Habel & K. F. Wender (Eds.), *Spatial cognition II: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge* (pp. 54-71). Berlin: Springer.

Cazzato, V., Basso, D., Cutini, S., & Bisiacchi, P. (2010). Gender differences in visuospatial planning: An eye movements study. *Behavioural Brain Research, 206*(2), 177–183. doi:10.1016/j.bbr.2009.09.010

Chowdhury, S., & Ceder, A. (2013). The effect of interchange attributes on public-transport users' intention to use routes involving transfers. *Psychology and Behavioral Sciences, 2*(1), 5–13. doi:10.11648/j.pbs.20130201.12

Conroy Dalton, R. (2003). The secret is to follow your nose: Route path selection and angularity. Environment and Behavior, 35(1), doi:107–131. 10.1177/0013916502238867

de Condappa, O. and Wiener, J., 2016. Human place and response learning: navigation strategy selection, pupil size and gaze behavior.Psychological Research, 80 (1), 82-93.

Ettema, D., Friman, M., Gärling, T., Olsson, L. E., & Fujii, S. (2012). How in-vehicle activities affect work commuters’ satisfaction with public transport. *Journal of Transport Geography, 24*, 215–222. doi:10.1016/j.jtrangeo.2012.02.007

Farr, A. C., Kleinschmidt, T., Yarlagadda, P., & Mengersen, K. (2012). Wayfinding: A simple concept, a complex process. *Transport Reviews, 32*(6), 715-743. doi:10.1080/01441647.2012.712555

Freksa, C. (1999). Spatial aspects of task-specific wayfinding maps: A representation-theoretic perspective. In J. S. Gero & B. Tversky (Eds.), *Visual and spatial reasoning in design* (pp. 15–32). Sydney: Key Centre of Design Computing and Cognition, University of Sydney.

Friman, M. (2010). Affective dimensions of the waiting experience. *Transportation Research Part F: Traffic Psychology and Behaviour*, *13*(3), 197–205. doi:10.1016/j.trf.2010.04.006

Garland, H. C., Haynes, J. J., & Grubb, G. C. (1979). Transit map color coding and street detail. *Environment and Behavior, 11*(2), 162–184. doi:10.1177/0013916579112002

Gärling, T., & Gärling, E. (1988). Distance minimization in downtown pedestrian shopping. *Environment & Planning A*, 20, 547-554. doi:10.1068/a200547

Gärling, T., Lindberg, E., & Mäntylä, T. (1983). Orientation in buildings: Effects of familiarity, visual access, and orientation aids. *Journal of Applied Psychology*, 68, 177-186.doi:10.1037/00219010.68.1.177

Gärling, T., Säisä, J., Book, A., & Lindberg, E. (1986). The spatiotemporal sequencing of everyday activities in the large-scale environment. *Journal of Environmental Psychology, 6*(4), 261–280. doi:10.1016/S0272-4944(86)80001-9

Golledge, R. (1995). Path selection and route preference in human navigation: A progress report. In A. U. Frank & W. Kuhn (Eds.), *Spatial information theory: A theoretical basis for GIS (COSIT '95)* (Lecture Notes in Computer Science, No. 988, pp. 207-222). Berlin: Springer.

Golledge, R. G. (1999). Human cognitive maps and wayfinding. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 1–45). Baltimore: Johns Hopkins University Press.

Guo, Z. (2011). Mind the map! The impact of transit maps on path choice in public transit. *Transportation Research Part A: Policy and Practice*, *45*(7), 625–639. doi:10.1016/j.tra.2011.04.001

Hayes-Roth, B., & Hayes-Roth, F. (1979). A cognitive model of planning. *Cognitive Science*, *3*(4), 275–310. doi:10.1207/s15516709cog0304_1

Henderson, J. M., Weeks Jr, P. A., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of experimental psychology: Human perception and performance*, *25*(1), 210.doi:10.1037/00961523.25.1.210

Hine, J., & Scott, J. (2000). Seamless, accessible travel: Users’ views of the public transport journey and interchange. *Transport Policy, 7*(3), 217–226. doi:10.1016/S0967-070X(00)00022-6

Hölscher, C., Tenbrink, T., & Wiener, J. M. (2011). Would you follow your own route description? Cognitive strategies in urban route planning. *Cognition, 121*(2), 228–247. doi:10.1016/j.cognition.2011.06.005

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological review*, *87*(4), 329-354. Doi:10.1037/0033-295X.87.4.829

MacGregor, J. N., Chronicle, E. P., & Ormerod, T. C. (2004). Convex hull or crossing avoidance? Solution heuristics in the traveling salesperson problem. *Memory and Cognition*, *32*(2), 260–270. doi:10.3758/BF03196857

MacGregor, J. N., & Chu, Y. (2011). Human performance on the traveling salesman and related problems: A review. *The Journal of Problem Solving, 3*(2), 1–29. doi:10.7771/1932-6246.1090

MacGregor, J. N., & Ormerod, T. (1996). Human performance on the traveling salesman problem. *Perception and Psychophysics, 58*(4), 527–539. doi:10.3758/BF03213088

MacGregor, J. N., Ormerod, T. C., & Chronicle, E. P. (1999). Spatial and contextual factors in human performance on the travelling salesperson problem. *Perception, 28*(11), 1417–1427. doi:10.1068/p2863

Meilinger, T., Hölscher, C., Büchner, S. J., & Brösamle, M. (2007). How much information do you need? Schematic maps in wayfinding and self localisation. In T. Barkowsky (Ed.), *Spatial cognition V – Reasoning, action, interaction* (pp. 381–400). Berlin: Springer. doi:10.1007/978-3-540-75666-8_22

Neider, M. B., & Zelinsky, G. J. (2006). Scene context guides eye movements during visual search. *Vision research, 46*(5), 614-621. doi:10.1016/j.visres.2005.08.025

Pomplun, M., Reingold, E. M., & Shen, J. (2001). Investigating the visual span in comparative search: The effects of task difficulty and divided attention. *Cognition, 81*(2), B57-B67. doi:10.1016/S0010-0277(01)00123-8

Raveau, S., Guo, Z., Muñoz, J. C., & Wilson, N. H. M. (2014). A behavioural comparison of route choice on metro networks: Time, transfers, crowding, topology and socio-demographics. *Transportation Research Part A: Policy and Practice, 66*, 185–195. doi:10.1016/j.tra.2014.05.010

Roberts, M. J. (2008). *Underground maps after Beck (2nd ed)*. Harrow Weald, UK: Capital Transport Publishing.

Roberts, M. J., Newton, E. J., Lagattolla, F. D., Hughes, S., & Hasler, M. C. (2013). Objective versus subjective measures of Paris Metro map usability: Investigating traditional octolinear versus all-curves schematics. *International Journal of Human Computer Studies, 71*, 363–386. doi:10.1016/j.ijhcs.2012.09.004

Sobel, K. V, Gerrie, M. P., Poole, B. J., & Kane, M. J. (2007). Individual differences in working memory capacity and visual search: The roles of top-down and bottom-up processing. *Psychonomic Bulletin and Review, 14*(5), 840–845. doi:10.3758/BF03194109

Van Orden, K. F., Limbert, W., Makeig, S., & Jung, T. P. (2001). Eye activity correlates of workload during a visuospatial memory task. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *43*(1), 111-121.

Vickers, D., Butavicius, M., Lee, M., & Medvedev, A. (2001). Human performance on visually presented traveling salesman problems. *Psychological Research, 65*(1), 34–45. doi:10.1007/s004260000031

Vickers, D., Lee, M. D., Dry, M., & Hughes, P. (2003). The roles of the convex hull and the number of potential intersections in performance on visually presented traveling salesperson problems. *Memory and Cognition, 31*(7), 1094–1104. doi:10.3758/BF03196130

Wiener, J. M., Ehbauer, N. N., & Mallot, H. A. (2009). Planning paths to multiple targets: Memory involvement and planning heuristics in spatial problem solving. *Psychological Research, 73*(5), 644–658. doi:10.1007/s00426-008-0181-3

Wiener, J. M., & Tenbrink, T. (2008). Traveling salesman problem: The human case. *Künstliche Intelligenz. KI und Kognition, 1*(08), 18–22.

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin and Review, 1*(2), 202–238. doi:10.3758/BF03200774