Cartographic design and usability of flow maps in public transport

René Vaartjes
rene@renevaartjes.com

MSc Thesis
Vrije Universiteit Amsterdam, UNIGIS

June 16, 2021

Student number: 2607432
Supervisor: Prof. Dr. J. Boter

Abstract

New construction of over 800,000 dwellings, large infrastructure projects and the increase in electric scooter-sharing systems and electric bicycles are some developments that will influence travel behaviour in the Netherlands. To keep the Netherlands accessible, transport experts have access to an increasing amount of data based on which they can formulate mobility policies and make decisions. Geographical Information Systems and web mapping applications enable transport experts to analyse large amounts of data with the help of geo visualisations. Research has shown that travel behaviour can be well analysed based on flow map visualisations.

However, from the studied literature, it is not completely clear which characteristics a flow map should meet to make mobility decisions effectively, efficiently and with satisfaction of the transport expert. Another omission is that a flow map usability test was not previously carried out among transport experts. This gap is closed with this study. The primary research question of this thesis is therefore: "Which cartographic design principles and visual variables of a flow map give transport experts a sound insight into the travel behaviour of citizens, helping to improve public transport services."

Based on qualitative research among 11 transport experts and 2 transport trainees, 16 static flow map variants and 3 dynamic or interactive flow maps were tested for usability.

This research reveals that geographical knowledge of the area is essential for transport experts to use flow map visualisation as a tool in decision-making processes effectively. The base map, information pop-ups, labelling and legend can play a supporting role in the map reading and orientation processes. Next, it is important to note that the size, shape and geographical position of the areas between which movement flows are depicted strongly influence the perception of the map reader. It influences, to a large extent, whether it is easy or difficult for a transport expert to interpret values or detect patterns.

The usability test also showed that policymakers prefer a flow map symbology with straight edges between pie chart nodes. It should present the number of movements between areas by using a straight edge with a clearly distinguishable colour per class. Incoming and outgoing flows per area are most clearly represented using a pie chart with two distinguishing colours that differ from the colours in the edges to avoid confusion.

The primary message of this research to scholars is to delve more deeply into the role of non-experts in developing user-oriented geo visualisations that enable transport experts to explore and analyse travel behaviour.

The author encourages GIS experts to involve transport experts at an early stage in the design process of flow maps symbology and map functions. This will result in a user-friendly flow map that allows the transport expert to make faster and better decisions to optimise the service of a mobility provider.

Keywords: flow map, line symbolisation, origin-destination, public transport, transit, movement behaviour, spatio-temporal visualisation, geo visualisation, cartographic design principles, usability evaluation

Acknowledgements
First, I would like to thank my colleagues Kelly, Patricia, Maddy, Harriët, Willem Kees, Jean Paul, Halmar, Richard, Naveen, Eddie and Reinier. They gave me the opportunity to test all visualisation variants based on their expertise in the field of public transport and mobility.

I would also like to thank Jeroen Rijsdijk of the City of Rotterdam and Jan-Kees van Elderen of the Metropolitan Region Rotterdam Den Haag for their contribution to my research. Their refreshing views and ideas helped me to look at the map reader differently and to develop new variants of flow map visualisations.

Special thanks go to my supervisor Jaap Boter (UNIGIS/Vrije Universiteit Amsterdam). I find it very impressive how you, despite all my twists and turns, always saw the road ahead when I was momentarily lost. Thank you so much for your useful feedback and excellent guidance during this project.

Finally, this journey could not have come to a successful end without the unbridled patience and encouragement of my wife Frances and our daughters Miró and Luna. Thank you for the opportunity to pursue my passion for cartography in this way.

Disclaimer

The results presented in this thesis are based on my own research at the School of Business and Economics Executive Education, of the VU University Amsterdam.

All assistance obtained from both individuals and organisations has been mentioned. In addition all published and unpublished sources are included in the bibliography. This thesis has not previously used for a obtaining a master degree.

Rotterdam, 16 June 2021

René Vaartjes

Table of contents

List of figures

List of tables

1 Introduction

1.1 Motivation

Transport experts of the Dutch urban transport operators (GVB, HTM and RET) have access to data on how many people travel between two stops. Public transport companies record the origin and destination data during check-in and check-out with a smart card (OV-chipkaart). Since a journey between two stops often has two directions of travel, multiple routes overlap, and many people are travelling at once, transport operators record large volumes of travel data daily.

On an aggregated level, public transport decision-makers need to know the number of travel movements between neighbourhoods. These insights are vital for optimising the timetable and the network. For example, knowing how the number of movements relates to the capacity is crucial for the work of the system. As a source, databases are used with anonymous check-in and check-out data, capacity and travel behaviour by car, bicycle, and public transport. Using reporting tools, decision-makers have it presented in tables (de Graaf, Veurink and Lodder, 2017; Onderweg in Nederland (ODIN), 2019). Because of the large volume of data, it is difficult to analyse it thoroughly. As a result, transport experts do not get proper insights into the anomalies and opportunities for improvement that occur within the city's public transport network. Since the systems register time and location during the check-in and check-out process, it is possible to learn more about the behaviour of travellers by applying geo visualisation. Both Stewart et al. (2016) and Shneidermann (1996) emphasise that visualisation of large volumes of travel data has advantages over using tables for data representation. Policymakers can get a complete understanding of the situation and its geographical context by looking at the overview of the origin and destination data between areas on a map. This helps to recognise patterns even without zooming in and filtering for a specific phenomenon.

Several authors analysed the work of public transport using the registered smart card data (Zhou, Corcoran and Borsellino, 2017; Song et al., 2018; Tao, Rohde and Corcoran, 2014). Using spatial software, an experienced user can see and analyse the movements of passengers within a certain period on a geographical map. One technique of visualising travel behaviour with a Geographical Information System (GIS) or mapping application is a flow map. It connects two or more locations (nodes) with intermediate links (edges). Field (2018) describes a flow map as a representation of a linear movement between places through either simple connectivity or mapping of magnitude. Flow maps can depict qualitative data (e.g., transportation mode) as well as quantitative data such as the number of passengers on a segment of the network. Visualising spatial interactions using flow maps helps to understand patterns and the spatial context (Koylu and Guo, 2017).

In daily practice, the use of GIS by urban transport operators is limited to visualising the network for travellers, managing assets, and mapping the infrastructure. Only in 2019, RET became the first Dutch urban transport operator to visualise travel behaviour based on smart card data in a GIS. Its transport experts still have little experience with using the system and visualising the origin and destination data. Also, it is not clear what is the best way of presenting the flow maps to facilitate decision-making.

In order to arrive at a complete solution for the information needs of transportation policymakers, the entire user-centred design life cycle (Kulyk et al., 2007; Rubin and Chisnell, 2008) has to be completed. This requires the participation of policymakers in the inventory of user requirements. However, this research focuses on one aspect of the evaluation phase in the user centre design cycle: the use of flow maps by transportation policymakers for decision-making. User research investigates how policymakers interpret flow maps and why they prefer certain forms of symbology.

During the literature review no relevant studies were found that combine the themes of public transport, flow map symbology and decision-making. Reviews of the previous research on the use of cartographic visualisations per individual theme conclude that the group of respondents was not representative. (Carpendale, 2008; Roth et al., 2017). For example, only a few studies analysed the users' visual perception of flow maps (Dong et al., 2018). Instead of utilising respondents who made real-life decisions based on geo visualisations, the samples comprised GIS experts or students.

Most previous studies on the use of spatial data by real decision-makers focus on static visualisations (Ozimec, Natter and Reutterer, 2010). Previously developed visualisation methods insufficiently use the dynamic and interactive solutions that incorporate the latest geo visualisation techniques to handle space, time and related attributes (Erskine et al., 2013; Robinson et al., 2017). This thesis attempts to fill this gap.

This user study addresses the lacunae mentioned above by conducting empirical research on how transportation policymakers perceive visual variables (edges and nodes) in presented flow maps. It explores which flow map design features should enhance the understanding of movement behaviour. Finally, symbology variants are proposed to contribute to usable flow maps for the benefit of transport policymakers to help them make better decisions. This should cause better accessibility of urban areas.

In this thesis, transport experts, policymakers, map readers and decision-makers are referred to as the same people. For readability, these terms are used alternately.

1.2 Research question

Deciding to improve services based on the vast amount of movement data is difficult for transport policymakers. If this data is visualised with flow maps, it is easier for them to gain insights into the origin and destination of travellers. These insights would enable policymakers to optimise their business operations. Unfortunately, it is not yet fully known what properties and symbology of a flow map work best for supporting transport experts in their decision-making processes. This observation leads to the following primary research question:

Which cartographic design principles and visual variables of a flow map give transport experts a sound insight into the travel behaviour of citizens, helping to improve public transport services?

To answer this question, this thesis attempts to answer the following sub-questions:

RQ 1 - How do policymakers perceive flow maps, and how do they derive information from the symbology used?

RQ 2 - What different forms of symbology are applied in flow maps and how capable they are of providing insights into movement behaviour?

RQ 3 - What visual properties and symbology are required from a flow map to help a policymaker make decisions on improving the service of a public transport company?

1.3 Scientific contribution

Never has research been conducted into the application of flow maps by public transport experts in decision-making processes. This study compares the insights obtained from the qualitative research with those from earlier studies aimed at GIS experts. The study aims to determine which flow mapping techniques and cartographic design principles enable policymakers to gain tactical knowledge of travel behaviour based on movement data more effectively and efficiently.

During the analysis of spatio-temporal movement data, humans interact with GIS. Not all public transport managers have extensive knowledge and experience with this technology. Based on previous research, it can be concluded that there is no scientific evaluation mechanism for the design and testing of visual representations that can bridge the cognitive deviations that exist between users and experts in the application field (He et al., 2019). This thesis carries out further cognitive experiments for the verification of which flow mapping techniques work better for user cognition.

Geo-scientists do not yet know enough about the application of flow maps by non-GIS experts and the way different designs of flow maps influence how users explore travel behaviour and substantiate decisions (Koylu, 2014; Koylu and Guo, 2017). Cartographers have not previously conducted empirical research based on which design principles of flow maps have been defined and tested among users (Jenny et al., 2018). Nowadays, flow maps are mainly designed based on the feeling and intuition of cartographers (Slocum et al., 2009; Dent, Torguson and Hodler, 2009). Cartographers should not rely only on their best judgement but also test and verify the flow map designs with the end-user. This study gives an impetus to this.

1.4 Practical contribution

In today's society, governments and businesses increasingly use data to solve complex issues. As an example, implementing a movement behaviour model (de Graaf, Veurink and Lodder, 2017) enables public transport organisations to analyse large amounts of travel data. Using information with the place and time references, also known as spatio-temporal data, helps to recognise patterns in the travel data and to explain specific phenomena such as movement behaviour.

Better insight into travel behaviour can contribute to the solution of one of the most significant mobility issues today: the poor accessibility of urban environments (Froehlich, Neumann and Oliver, 2008; Eindrapport Analyse- en Oplossingsrichtingenfase MIRT-onderzoek Bereikbaarheid Rotterdam Den Haag, 2017) during rush hour and major events or in case of unusual weather conditions. Geo visualisation of flows based on origin and destination data would help public transport companies to improve their services. Public transport that is more in tune with passengers' travel behaviour would encourage citizens to use public transport more often. This would lead to better accessibility of the environment.

From an economic and social point of view, public transport experts need to know between which neighbourhoods in the service area have the largest travel flows. By comparing the intensity of a network' use with its capacity, it would become clear which routes need adjustments in frequency and what number of standing and seating places is required to improve the service.

By adding the temporal factor to spatial information, it would become clear whether a capacity problem occurs continuously or only at certain times. It would also be possible to observe deviations in travel behaviour in the public transport network during a day. Certain events such as rain or a music festival can be linked to observed variations. By looking critically at flow maps with origin and destination data of similar circumstances, it is possible to respond to the transport needs of citizens more effectively and efficiently.

1.5 Structure of the thesis

The first chapter argues the usefulness of research into the application of flow maps in the public transport sector. The central question and the underlying sub-questions are identified. Chapter one concludes with the scientific and practical relevance of this research.

Chapter two describes the theoretical framework. An inventory of previously produced flow maps provides insight into possible design directions and forms of symbology. Next, related research is discussed on how decision-makers perceive different forms of flow map symbology. Subsequently, research into the influence of symbol size, shape, colour, value, orientation, arrangement, texture, focus and location on the cognitive load of non-GIS experts and decision performance will be reviewed. The chapter ends with the analysis of the usability of flow maps.

Chapter three "Methodology" is divided into four sub-topics: "Research design", "Participants", "Geo visualisations and equipment", and "Data analysis". In the subsection "Research design", the advantages and disadvantages of the applied methods of qualitative research are discussed: the interview, the usability test, and the post-test questionnaire. The Participants section deals with the research population. Next, "Geo visualisations and equipment" briefly describes the tools and materials used in the empirical research. The tested flow map symbology variants are described in more detail in Appendix F. The final section "Data analysis" explains how the input from the interviews, usability tests and post-test questionnaires were recorded, coded and analysed. It explains how the knowledge of the service area and the network of the public transport company among the participants can be used to establish the relationship with the user performance during the usability test.

The results of the qualitative research are described in Chapter 4. The first subsection clarifies what information and what level-of-detail policymakers use to make decisions to improve public transport. Then the feedback on the different visualisation variants collected during the usability test is discussed. Following this, the mental effort of the respondents in applying the different flow map variants in the decision-making process is addressed. In the subsection "Static flow maps versus dynamic flow maps", the advantages and disadvantages mentioned by the participants are presented. Finally, the relationship between geographical knowledge and knowledge of the public transport network and the performance of the participants is defined.

In the last chapter, the insights from the literature review and the empirical research are brought together. It answers the research question which symbology a flow map should meet to support policymakers in their decision-making processes. At the same time, advice is given to map designers on how transport experts can best be involved in creating of a flow map.

This thesis concludes with a summary of the limitations encountered during the COVID-19 pandemic and the associated research design. Fortunately, this offers sufficient starting points for future research to repeat the existing research via a quantitative method or to focus on the applications of dynamic flow maps.

2 Literature review
Until now, only limited research has been done on the application of flow maps in visualising movement behaviour. Studies carried out mainly focus on the visualisation issues and hardly on how map readers utilises and understands flow maps.

This literature review therefore focuses on both the design of flow maps and the experience and application by the user group. These are policymakers at public transport companies and government authorities who make decisions based on movement behaviour in order to improve services and the network.

The first section of this literature study discusses the different flow maps. It critically assesses the earlier research into different kinds of flow map visualisation to determine its applicability for mobility questions. The second section discusses how a visual variable system underlies the symbology of a flow map. It proposes various forms of flow map symbolisation and assesses their readability and applicability in a GIS or mapping applications. Subsequently, the effect of visual variables on a policymaker's cognitive load is discussed. The literature review concludes with an analysis of how transport experts interpret map symbology and base their decisions on it.

2.1 Categorising flow maps
Transport experts use flow maps to visualise the number of movements of passengers and vehicles based on the origin and destination points at a given time or within a certain period. Besides visualising quantitative data, a flow map also can show qualitative data. For example, a bivariate flow map uses various hues to visualise the type of transport and utilises lines of different width to show the volume of passengers travelling a route (Field, 2018). Moreover, multivariate flow maps are capable of presenting two or more variables in a map with a symbology that visually encodes data combinations (Field, 2018). Combining quantitative and qualitative data complicates the visualisation of links between stops or areas, but also gives the user more context.

A flow map comprises edges and nodes. An edge is a vector path connecting two nodes (Stanford University and Steiner, 2019). A node represents the origin or destination of a journey. On a map this can be, for instance, a centroid of a neighbourhood or a stop. The type of network over which a person or a vehicle travels can be different, such as a waterway, a road, or a rail network. A flow map can follow exactly the existing infrastructure and nodes, or demonstrate relationships by means of the celestial latitude between nodes. In the literature various methods are proposed for visualising flow maps. The following subsections discuss to what extent they can visualise movement behaviour.

2.2.1 Continuous flow map
Continuous flow maps (Slocum et al., 2009) are mainly used to display uninterrupted movements and directions, such as the wind or water flow (Slocum et al., 2009). Kwan (2012) holds the opinion that this type of flow map is not suitable for visualising a movement behaviour that involves two-way flows. However, for the visualisation of unstructured and abrupt pedestrian traffic in a busy underground station, each passenger can be assigned a symbol with a graphic effect. Kim et al. (2018) show that discrete data can be displayed as continuous data by using the kernel density estimation technique. Heat maps of passenger movements are extracted to a flow map using a gravity model (Kim et al., 2018). In this continuous flow map, glyphs with an arrow-shaped end can animatedly show the passenger flows through a station. By changing the value or size of the glyph, an increase of passengers or the walking speed at a specific moment in time can be visible in animation.

2.2.2 Network flow map

A network flow map can depict the number of people travelling from one area to another in a particular way at a given time. Travel behaviour between areas is represented using edges that adopt certain visual properties depending on the type of movement or intensity. Edges connect nodes, centroids of the visualised neighbourhoods. The nodes show the total number of incoming and outgoing people.

Parks (1987) reveals that the emphasis is placed on network patterns and to a lesser extent on the exact values represented by the edges between the nodes. In a public transport network, except for underground metro lines, road or rail segments rarely run as the geodesic distance between stops. A simplified representation of movement between neighbourhoods makes it easier to visualise travel behaviour and to determine the relationships between nodes. It takes the user less time to recognise nodal relationships based on edges and to read the correct values more accurately (Xu et al., 2012). The disadvantage of this approach is that at individual line level (bus, tram or metro) no insight is gained into travel behaviour. This can be solved by creating a more detailed flow map with a larger scale.

2.2.3 Radial flow map

A radial flow map can be used to show which destinations can be accessed from a transit hub. Based on the thickness of the lines in the spoke pattern, it is immediately clear between which nodes the most significant number of movements takes place. If straight lines connect the origins and destinations, this is also called a desire line map (Dent, Torguson and Hodler, 2009).

2.2.4 Distributive flow map

A sub-type of a radial flow map is a distributive flow map (Parks, 1987); a flow map via spiral trees (Buchin, Speckmann and Verbeek, 2011) or flow tree (Han, Clarke and Tsou, 2017). They allow tracing all branches (edges) from one node (origin), showing all destinations that were explored. The width of the branches designates the volume of travellers. With flow trees, it is challenging to read flow volumes because the branches do not provide direction, and at the ends of the branches, the thickness of the edges does not represent the volumes correctly. Attempts to display many branches to different destinations within a small area result in the clutter in distributive flow maps (Phan et al., 2005).

2.2.5 Animated and interactive flow maps

Thanks to the availability of interactive user interfaces, web mapping, and GIS, it is now possible to plot the data on a map and implement animation control to depict each time step in data visualisations (Han, Clarke and Tsou, 2017); (Kim et al., 2018).

Han, Clarke and Tsou (2017) show that most animated maps that present movement behaviour of individuals or objects over time do not show an overall pattern of volumes or a comparison of volumes between different periods. This is a remarkable observation. Some animated flow map solutions are incapable of showing the overall picture. However, a GIS or a visual analytics environment are able to present an entire image or comparison through time. They can achieve this not only by using maps but also depicting origin-destination matrices, tidal flows, or stills from an animated sequence (Wood, Slingsby and Dykes, 2011). An animation can also show the trajectory of a variable in time and might be paused to gain a better understanding of underlying values and aspects such as flow velocity (Field, 2018).

The Animated Flow Mapper developed by Han, Clarke and Tsou (2017) avoids visualisation issues with overlapping arrows pointing to the direction of a movement and occlusion of overlapping edges.

Relations between origins and destinations become more clear thanks to the use of thin dashed lines of equal thickness. Animation of the line visualises the direction, while saturated colours and the speed of the animation represent the flow volume (Han, Clarke and Tsou, 2017). The research will show whether users can correctly read the magnitude and direction of an animated dotted line with a specific colour and saturation.

A considerable disadvantage of such visualisations is that their success depends on the reader's ability to establish the relationships between elements in space by means of continuous inspection of the map. A solution to this problem is to offer an online tutorial that demonstrates the user the application's potential step by step. The advantage of interactivity is that users can focus on specific areas of interest and glean finer details that would otherwise be hidden in a static summary of overall trends (Stephen and Jenny, 2017).

2.2.6 Summery

Flow maps enable policymakers to visualise and analyse movement behaviour. The discussed flow map types all offer, to a greater or lesser extent, the possibility of visualising movement data. In this study, for reasons of time and space, it was decided to only examine the application of network flow maps and interactive flow maps. The above analysis shows that both methods are best suited to depict travel behaviour between nodes within the service area of a public transport operator.

In order to display movement data effectively, not only the correct choice of flow map type is important. A cartographer must know of the challenges involved in using a flow map by a non-expert as described in the next section. Knowledge of related design properties as discussed in the subsequent sections is essential because it influences the policymaker's cognitive effort and the decisions to be taken.

For the qualitative research, this means that static flow map variants (See Appendix C - Flowmap_0, Appendix D - Flowmap_36 and Flowmap_37) were designed. The flow map variants in flowmap_0 allow the participant to choose and substantiate why a pure network flow map, a distributive flow map or an intermediate form is best able to visualise travel behaviour. Flowmap_36 and 37 test the usability of the different visual variables described in subsection 2.5.1 and the egde and node variants discussed in subsections 2.6.1 and 2.6.2.

In the user research, two dynamic flow maps (See Appendix C - D1_blue_flow_map and D2_dynamic_flow_map) are used to investigate which interactive format can depict a comparison between periods. Flow_map_51 (Appendix D) gives insight into the motivation of transport experts for the use of static or dynamic flow maps.

2.3 Flow mapping issues

During the production of flow maps, visualisation issues can arise, which can make it difficult and time-consuming for users to derive the right information. This section discusses such issues and feasible solutions. The challenges specific to the design and visualisation of point and line symbols are explored in sections 2.6.1 and 2.6.2. The gained insights contribute to the selection and design of flow map symbology for empirical research.

2.3.1 Issues

In city centres, the density of public transport networks is often high. Suppose a decision-maker wants to gain insight into the occupancy rate of the lines and the number of passengers boarding and disembarking at all stops in the centre. In that case, visual clutter will occur (e.g. the city centre of Rotterdam). It is difficult for public transport experts to make a decision or develop a policy based on the information presented in such a way.

Occlusion of edges and nodes causes essential information to be missed or overlooked. Salience bias attracts the focus of the user to a flow map's elements that are less important for obtaining knowledge. The overload of information, because of the accumulation of lines, head arrows, dots in different colours and widths on top of a base map makes it extra challenging to fathom intricate patterns (Dong et al., 2018).

2.4.2 Solution directions

The solutions that scientists have suggested include aggregation of map elements, automatic clustering of nodes and edges (Phan et al., 2005); bundling of spatial generalisation and aggregation of juxtaposed edges (Buchin, Speckmann and Verbeek, 2011); sampling (Zhou et al., 2019) and edge bundling (Zhou et al., 2013). Data aggregation facilitates the analysis and visualisation of travel behaviour (Giannotti and Pedreschi, 2008). Incidentally, traditional flow map generalisation methods may cause in the modifiable areal unit problem (MAUP) (Openshaw, 1984) and, therefore, can represent erroneous patterns (Guo and Zhu, 2014).

By first showing an overview of the service area to be analysed, it is possible to zoom in on the nodes and edges that deviate strongly from a pre-defined standard. If zooming in results in an overload of detailed information and an overlap, techniques such as brushing (Wood, Dykes and Slingsby, 2010), filtering (Boyandin, Bertini and Lalanne, 2010) and linking (Guo, 2009) can offer a solution.

In a visual analytics environment, the mentioned data cleaning techniques and various data visualisation forms can be combined. The user selects elements in the map and, in addition to the flow map, additional attribute information is presented in a time bar, origin-destination matrix, space-time cube, animation, or line graph. This solution not only shows the movement behaviour but also extracts patterns and provides new insights in this way because every form can make use of its strong presentation properties.

2.4.3 Summary flow map issues and solutions

Cluttering and occlusion create serious limitations when consulting and analysing a flow map. Aggregation, clustering, brushing and filtering are techniques that offer a solution to these issues. These methods show their fullest potential in dynamic flow maps. For this study, travel by car, bicycle and public transport were aggregated per neighbourhood.

For the qualitative research, this means that the described issues that occur during visual exploration and knowledge gain are tested with the help of different flow maps and symbolisation by transport experts (see Table 1). The mentioned visual operators are explained in Section 2.8.2 - Phase 5.

Flow map issue	Visualisation operator(s)	Flow map design variant (Appendix C and D)
Legibility	Detection and location	Flowmap_18, Flowmap_38 and Flowmap_39
Clutter	Discrimination. identification	Flowmap_0, Flowmap_18 and Flowmap_36
Occlusion	Discrimination. identification	Flowmap_0, Flowmap_18 and Flowmap_36
Salience bias	Comparing	Flowmap_3, Flowmap_8, Flowmap_12, Flowmap_20 and Flowmap_49
Information overload	Correlating and decision-making	Flowmap_8, D1_blue_flow_map and D2_dynamic_flow_map, Flowmap_25

Table 1: Flow map and symbolisation variants introduced in the qualitative research to test visualisation issues during the execution of knowledge exploration and decision-making tasks.

2.4 Flow map layout

Before it can be determined how a decision-maker can use a flow map as an effective instrument to improve the service of a public transport company, the elements underlying a flow map must first be made clear. The crucial design aspects of a flow map include map projection, map scale, labelling, figure-ground, the design of the legend, perceptual grouping to distinguish objects, line scaling and symbolisation (Dent, Torguson and Hodler, 2009). The first five aspects are dealt with in the following sub-paragraphs. Because sections 2.7 and 2.8 will show that visual variables have a major influence on a transport expert's cognitive effort and the decision-making process, the studied literature for this subject is discussed separately in sections 2.5 and 2.6.

2.4.1 Projection and scale

The map scales in the literature studied vary from maps at the national level to street level. A large-scale map of course offers more space to incorporate detail and flow map symbology. A disadvantage is that the overview disappears more quickly if too much is zoomed in on a location.

The service area of a Dutch urban public transport company is relatively small. Therefore, the applied scale of a flow map to depict movement is medium to large (1:10,000 to 1:100,000). The scale on which information is displayed on the map is relevant. In the qualitative research, transport experts are asked when they require what scale and level of detail to derive the right information to base decisions on (see Appendix C - Flowmap_19, D1_blue_flow_map and D2_dynamic_flow_map).

The impact of a map projection on this scale is small and is not considered in this study.

2.4.2 Labelling

Using labels at nodes or edges can help the user orient themselves or directly read the exact value of line attributes. Of course, it is essential that labels do not disrupt the flow map's symbology, because it will interfere the legibility.

The importance of orientation based on labels in a flow map is tested in the qualitative research by map readers (see Appendix C - D1_blue_flow_map and D2_dynamic_flow_map and Appendix D - Flowmap_48).

2.4.3 Figure-ground

To orient and to comprehend the context, a flow map also has to show essential elements of an underlying reference map. For example, the contrast between land and water is essential (Dent, Torguson and Hodler, 2009). Although the flow lines have the highest informational and, therefore, visual priority when positioning the edges of the flow map, the cartographer also must consider the space taken up in the map.

For qualitative research, this means that different base maps (topographic, satellite and grey canvas maps) are tested for readability, contrast and their suitability for orientation (see Appendix D - Flowmap_35).

2.4.4 Legend design

The legend of a flow map is the crucial link between the cartographer and the map reader that explains the map's symbology (Dent, Torguson and Hodler, 2009). The presentation of edges in the legend must correspond precisely with how the edges are shown in the map. If the classification of values is applied, the class boundaries in the legend must be adopted. Colours used in the flow map can be represented in the legend utilising rectangles with fills as applied in choropleth maps.

In an interactive flow map, the GIS expert can add explanations of the symbology by using pop-ups or layovers. However, this puts an extra load on the cognitive ability of the map reader.

Different forms of legend are tested with the participants in the user studies (see Appendix C – Flowmap_2, Flowmap_5, Flowmap_7, Flowmap_10, Flowmap_11, Flowmap_13, D1_blue_flow_map and D2_dynamic_flow_map and Appendix D- Flowmap_47)

2.5 Visual variables

Space-time as geographical phenomena is well-suited for representing travel behaviour. Although the focus of this thesis is on the application of flow maps, many of the findings in this research can also be applied to the visualisation of movement behaviour via space-time cubes.

The thematic symbols, lines (edges) and points (nodes) are the essential components in a flow map that visualise travel behaviour. So far, only limited research has been done on the effectiveness of flow map design principles and applied symbology. Research into the performance of applied symbology, user preferences, and user behaviour as a result of applied design more often focuses on graph drawing (Purchase, 2014). However, it is possible to derive design rules from this design discipline that can also be used for the production of flow maps. The correct symbolisation of nodes and edges should minimise crossings, overlaps, and distortions (Phan et al., 2005). What is striking in the literature reviewed is the divergence of views on visualising attribute values, directions, and edges.

Besides to the variables described in the following sections, a distinction can be made between selective and associative visual variables. A visual variable is selective if all symbols can be easily isolated based on, for example, colour hue (Garlandini and Fabrikant, 2009). A red-coloured symbol stands out among blue-coloured symbols.

Associative visual variables are grouped by the map reader based on specific visual characteristics, for example, symbols with the same shape but with different sizes. Dissociative visual variables facilitate the detection of visual variations among the signs, compared to visually distinguishing groups of similar symbols across the rest of variables (Garlandini and Fabrikant, 2009).

Section 2.5.1 discusses the visual variables for static maps. Section 2.5.2 examines the variables for dynamic and interactive maps.

2.5.1 Visual variables - static maps

One of the founders of signs and symbols in cartography, Jacques Bertin, in his work "Semiology of Graphics: Diagrams, Networks, Maps" (Bertin, 1983) has laid an essential foundation for the visualisation of information (Field, 2018). Bertin has created a grammar for cartography using retinal, or visual variables, which has been later extended by other cartographers and scientists.

This section includes an overview of the inventoried visual variables for static maps. For each visual variable, it is described to what extent its symbology can represent nominal, ordinal, or numerical data. Figure 1 summarises the suitability of the visual variables found in the literature for visualising movement behaviour.

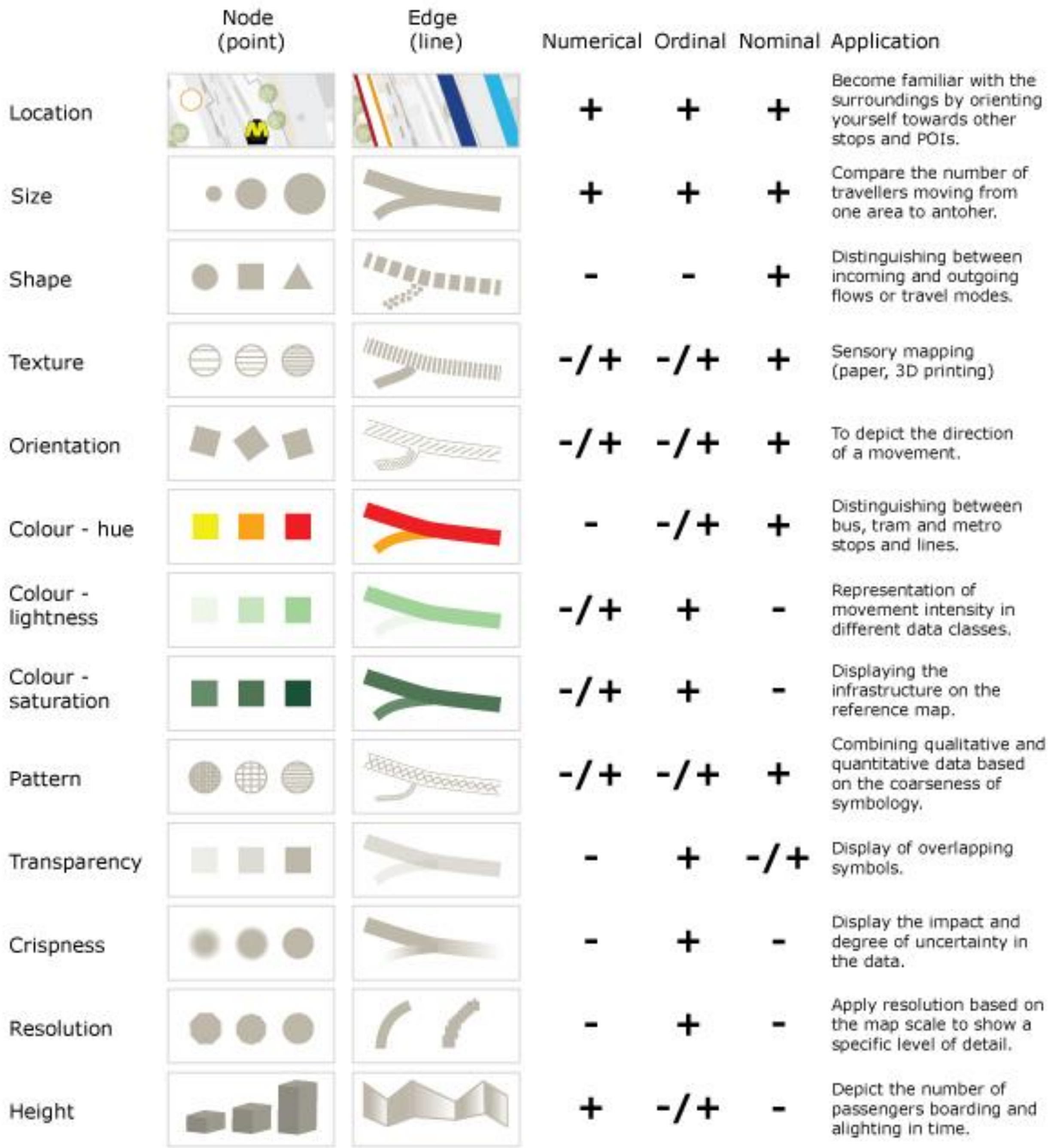


Figure 1: Static visual variable syntactics (after MacEachren (1995); Kraak and Ormeling (2010); Field (2018))

Location

Understanding of the geographical position of a neighbourhood, stop, or line in the service area of a public transport company is of paramount importance when analysing movement behaviour. An area, stop or line is not a stand-alone phenomenon, and its use is influenced by other neighbourhoods, stops and lines and its surroundings. A location can be represented by a point, line, area or volume. In this study, the focus is on point and line symbols. Neighbourhoods are represented by a centroid. The geographical area of a neighbourhood is demarcated in the flow map by district boundaries. To truthfully show the location of a feature, there is only limited scope for moving a symbol on a map, especially if there are multiple map elements next to or on top of each other. The bundling of nodes and edges or the use of interactive functions such as filtering may offer a solution.

Size

Utilising size as a visual variable allows to indicate the relative importance of a feature on a map (Field, 2018). The size of a point or the thickness of a line visualises the underlying quantitative value. It is limited by the extent of the map and the influence of the size on the readability. Field (2018) uses 0.2 millimetres as the minimum size of a point to remain legible. Legibility, however, also strongly depends on the vision of the map reader, the resolution and the quality of the computer screen.

It can be difficult for users to distinguish differences in point size or line thickness. By classification, a greater distinction can be achieved between the displayed symbology. For example, size also can be combined with other visual variables. It must be noted that in such a case, the size will continue to dominate the user's perception (Bertin, 1983).

Since a point can be composed of several parts, each part can also have a separate size. Through illustration, a point symbol can comprise four different planes in which each plane visualises the number of people entering a direction or the number of people exiting from a direction.

Shape

An infinite number of shapes can give map elements an infinite number of meanings (Bertin, 1983). When displaying a stop or station, it is worth checking whether a geometric or mimetic format best conveys the meaning to the user. With a geometric symbol, a circle provides the greatest recognizability because of the person's actual experiences with paper line network maps. Alternatively, arrows incorporated in a node symbol representing incoming and outgoing passenger flows can be tested for comprehensibility.

Through different line styles, such as dots, dashes, and their combinations with uninterrupted lines, different modalities can be distinguished. For example, temporarily closed roads can be displayed via dotting.

Shape as a visual variable can only display nominal data. Users cannot derive ordinal or numeric data based only on a deviating shape without consulting the legend (Field, 2018).

Texture

Texture or spacing (Slocum et al., 2009) refers to the pattern of graphical marks in a unitary area of a symbol (Field, 2018). By using the spacing and arrangement of pattern or graphical marks, symbols distinguish themselves from each other. The population density of a neighbourhood can be displayed in this way. Depending on the hue of the graphical marks and the distance to each other, the symbol shows lighter or darker. The resolution of the computer screen, expressed in pixels per inch (ppi) determines, to a large extent the number of textures to be observed. Users can easily distinguish a maximum of three to four different textures in a linear representation. For a point representation, two or three different values can be recognised if the symbol is large enough (Bertin, 1983).

Orientation (angle)

Components in a point symbol can have an infinite number of orientations (Bertin, 1983). For a stop and a line, the direction of travel can be represented by adding an arrow element. Differentiation between lines can be created by routing the same pattern. Bertin (1983) shows that in linear representations, a maximum of two different variants can be applied on a map in order to perceive the difference. Rotation does not work well for mimetic symbols because it reduces readability (Field, 2018).

Colour - hue

Hue is one of the three components of colour that is defined by the dominant wavelength of visual light (Field, 2018). According to Slocum et al. (2009), hue can be applied to represent quantitative phenomena. Field (2018) holds the opinion that hue is not distinctive enough to represent numerical data effectively.

Hues such as green, red, and blue can be applied especially well in symbols that visualise qualitative phenomena, nominal data and, to a lesser extent, ordinal data (Field, 2018).

Colour - lightness (value)

Value is the ratio between the total amounts of black and white perceived on a surface as grey-scale or any hue (Field, 2018). Low reflectance of light results in darker hue values. High reflectance of light results in light hue values. A scheme of light to dark shades can contain a maximum of seven classes in order to maintain the distinction. The smaller the area of a symbol (map element) is, the more significant becomes the reduction in the number of observable classes (Bertin, 1983). Even though a colour's value is less successful than line thickness in providing the user with insights into movement intensity, this study examines its effectiveness.

Colour - saturation (chroma)

The mixture of grey and a pure hue is called saturation (Slocum et al., 2009). Saturation is the intensity of a hue as lightness is held constant. High-resolution screens stimulate the use of more saturated colours to make elements stand out more from the map (Field, 2018).

Pattern

One or multiple pattern fills can be applied to lines to distinguish between features. To a large extent, the weight and orientation of a line pattern determine the distinctiveness of the element. A pattern can also be created by using transparency that extends into the arrowhead of a line (Field, 2018).

Transparency

Transparency stands for the amount of light that an object lets through. The opposite phenomenon, opacity, indicates how much light an object blocks (Field, 2018). Transparency increases the possibilities to diversify the options for map symbols. The visual hierarchy of a symbol in relation to other symbols is determined by the degree to which it is more or less transparent. Bivariate or multivariate flow maps can show symbols with different transparency values on top of each other in separate layers. The combination of layers with various symbols and transparency on top of each other can show where the intensity or values of features are the highest or lowest.

Transparency can well show ordinal data, although it is far less suited for displaying nominal data. Field (2018) suggests that transparency is incapable of representing numerical data. However, in a separate layer, a transparency percentage can be given to a line. If there are several lines at precisely the same position, they can be displayed stacked. In this way, the occupancy rate of a trajectory with multiple lines can be made clear.

Crispness

A fuzzy line comes across less distinctly on the map than a sharply drawn one. A blurred map symbol is often used to depict uncertainty.

Blurred or fuzzy lines cannot represent nominal and numeric data. Therefore, the degree of the crispness of a line can represent ordinal values (Field, 2018).

Resolution

The resolution of symbols is expressed in the spatial precision with which data is displayed on the map. In a GIS, a point or line feature can be constructed using a grid consisting of pixels or in vectors comprising nodes and edges. Since a map in a GIS can be composed of multiple layers, each layer can have a different resolution and suggest different levels of generalisation. The data displayed in higher resolution with more detail and higher spatial precision is perceived as more notable by the user. Different levels of detail and accuracy enable the cartographer to create various visual levels (Field, 2018).

Height

Besides x and y coordinates that form a surface, a z value gives an extra dimension that can visualise a positive or negative value of a feature through extrusion.

Because surfaces with higher values can overshadow surfaces with lower values, interactive functions are needed to incorporate them. Values become visible by rotating the view, zooming in and out and panning the map to view 3D symbols from all sides.

Static visual variable	Visualisation operator(s)	Flow map design variant (Appendix C and D)
Location	Detection and location	Flowmap_18, Flowmap_23 , Flowmap_38 and Flowmap_39 and Flowmap_40
Size	Detection, discrimination, identification, comparing, ranking, correlating and decision-making	Flowmap_1, Flowmap_4, Flowmap_6, Flowmap_9, Flowmap_11, Flowmap_13, Flowmap_17, Flowmap_20, Flowmap_24, Flowmap_36, Flowmap_38, Flowmap_41, Flowmap_42, Flowmap_43, Flowmap_44, Flowmap_45, Flowmap_46, D1_blue_flow_map and D2_dynamic_flow_map
Shape	Detection, discrimination, identification, categorizing and comparing	Flowmap_0, Flowmap_1, Flowmap_4, Flowmap_6, Flowmap_9, Flowmap_18, Flowmap_36, Flowmap_37, Flowmap_39, Flowmap_41, Flowmap_42, Flowmap_43, Flowmap_44, Flowmap_45, Flowmap_46, D1_blue_flow_map, D2_dynamic_flow_map and Flowmap_50

Colour - hue	Detection, discrimination, identification, comparing, clustering, correlating and decision-making	Flowmap_6, Flowmap_9, Flowmap_17, Flowmap_18, Flowmap_19, Flowmap_21, D1_blue_flow_map, Flowmap_36, Flowmap_37, Flowmap_41, Flowmap_43, Flowmap_45 and Flowmap_46
Colour - lightness	Detection, discrimination, identification, comparing, clustering, ranking, correlating and decision-making	Flowmap_1, Flowmap_4, Flowmap_11, Flowmap_13, Flowmap_17, Flowmap_19, Flowmap_20, D1_blue_flow_map and D2_dynamic_flow_map, Flowmap_17, Flowmap_37, Flowmap_42, Flowmap_44 and Flowmap_46

Table 2: Tested static visual variables for the visualisation of movement behaviour

The visual variables listed in Table 2 can have a major impact on how a policymaker identifies, analyses and applies movement data in the decision-making process. In the qualitative research, transport experts are tested whether they show similar or deviating behaviour when applying the mentioned visual variables compared to other user types in previous research.

2.5.2 Visual variables - dynamic maps

The term "dynamic maps' refers to animated and interactive maps. Bertin (1983) reveals in his work "Semiology of graphics: Diagrams, Networks, Maps" that the visual variables listed are not suitable for dynamic maps. He notes that movements in maps captivate the user's perception so strongly that they overshadow other visual variables. The empirical research in this study should reveal whether this statement also applies to non-experts, such as policymakers.

Field (2018) considers that the application of static visual variables alone in creating a dynamic map is not sufficient. Both Field (2018) and MacEachren (1995) recommend using additional dynamic visual variables. Figure 2 summarises the suitability of the visual variables found in the literature for visualising nominal, ordinal, and numerical values.

As a subset of dynamic maps, interactive flow maps can reveal a wide variety of data. The hierarchy in the data is made visible or invisible by zoom, pan, filter and query tools. A mouse over and click function shows attribute values of a node or edge only when touched. This prevents cluttering in the map.

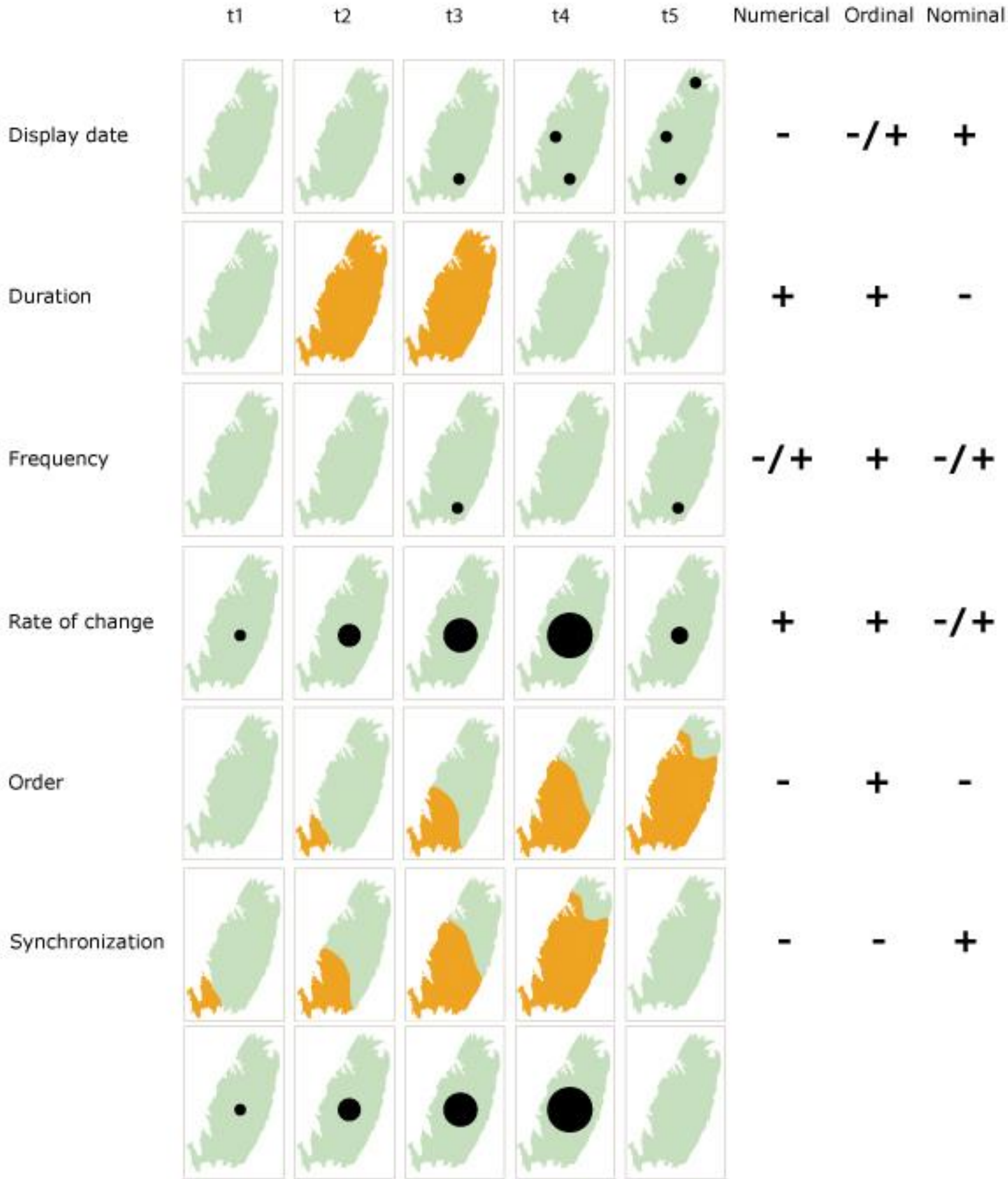


Figure 2: Dynamic visual variable syntactics syntactics (after MacEachren (MacEachren, 1995); Field (Field, 2018))

MacEachren (1995) states that the power of movement can be applied as an excellent visual variable because it includes the two indispensable variables, "time" and "space." In addition, he holds the opinion that map readers can distinguish several variables in a map and that elements which change shape, size, or colour in the map attract extra attention. According to DiBiase et al. (1992), mapping time has three different visual variables: duration, rate of change, and order. Later, MacEachren (1995) has added frequency and synchronisation.

Display date (moment)

Display date shows the user when a phenomenon occurs for the first time or when a change in status occurs. To gain insight into the number of people boarding and alighting in a particular neighbourhood, an animated point symbol indicating the period can be applied.

Nominal data can be displayed using the visual variable display date on an animated map. Ordinal data can be displayed using display date less successfully. Numeric values are entirely unsuitable to be visualised in this way MacEachren (1995).

Duration

Duration refers to the length of time that a frame of an animation is displayed (Slocum et al., 2009). The higher the frame rate of animation is, the more gradually the transition between changing states is shown. A scene in an animation consists of a series of frames that do not change. A sequence with subsequent scenes forms an episode. An episode can comprise a recurring time cycle, e.g. a day in the timetable of a public transport company or traffic during rush hours and off-peak hours.

Duration can display both numerical and ordinal data. Duration is not suitable for displaying nominal data on a map (MacEachren, 1995).

Frequency

The number of identifiable states of a feature can be displayed over time (Slocum et al., 2009). For public transport, the trip frequency per line can be animated. This information can be visualised at the same time as the number of travellers.

In qualitative research, a snapshot of a dynamic flow map is tested for comprehensibility. Through different colour shades and line thicknesses it is investigated whether transport experts can identify differences and to point out the best performing route (see Appendix C - Flowmap_17).

Rate of change

Slocum et al. (2009) define the rate of change in an animation as the magnitude of the transition between frames or scenes and the duration of each frame or scene. The geographic position or the properties of attributes may change over time. These changes can be slow, constant, fast constant, or flourishing (MacEachren, 1995).

For qualitative research, this means testing the ability of transport experts to understand a flow map with several changing variables (see Appendix C - Flowmap_20).

Order

Frames or scenes are usually presented in a logical order. New insights can be obtained by rearranging the frames or scenes (DiBiase et al., 1992). By comparing the intensity of movements between areas for several Saturdays in a year, patterns can be observed that would otherwise remain hidden.

Synchronisation

Two or more different spatial-temporal data sets can be synchronised by matching the dates exactly. Exploratory visualisations, based on the juxtaposition of spatial-temporal phenomena, can reveal hidden patterns (MacEachren, 1995). A specific example would be a relationship between the number of passengers boarding and disembarking at a stop and the occupancy rate on a specific route.

2.5.3 Summary of the application of visual variables in flow maps

In this section, the most important visual variables that can be applied when creating a flow map are discussed. For the qualitative research, this means that the visual variables: location, size, shape, colour (hue), colour (lightness), frequency and rate of change are applied in flow map prototypes and are tested for usability by transport experts.

The qualitative research should prove whether the extra effort that map readers have to make to familiarise themselves with the interactive flow map outweighs the benefit of the richer provision and clarity of the information.

By combining the preferred visual variables with variables suitable for displaying ordinal or nominal values, the cartographer has access to a comprehensive toolbox to visualise movement behaviour. In the next section, the visual variables examined are reflected in the two fundamental building blocks of a flow map: nodes and edges. The features and application of these two flow map symbols will be further assessed.

2.6 Flow map symbolisation

This thesis focuses on how transport experts read and interpret flow map data in order to make the right decisions. A point and a line are the essential feature types that, in combination with the previously mentioned visual variables, should form a readable and interpretable geo visualisation. Symbols can represent attributes as of static elements on the map or can be displayed as dynamic elements.

Dynamic symbols change when the attribute values alter or when the map's scale changes and affects the visual properties of a symbol. Adjustments can take the form of fill and stroke colour, size, animation such as blinking or in the rate of change (Gar-on et al., 2001). Depending on his information needs and preferences, a user can also modify the representation of symbols in a dynamic map.

Assigning the right meaning and value to a symbol can occur on different levels. This can be by recognition of the shape, by a knowledge of the location or environment, or because the map reader comprehends the meaning of a symbol with the help of an adjacent symbol (Ooms, De Maeyer and Fack, 2014).

Knowledge of how symbology works is a prerequisite for understanding how a transport expert derives information from a flow map. The properties and readability of a symbol determine to a large extent whether a policymaker applies a flow map in the decision-making process. In this section, the relevant literature on point and line features is discussed.

2.6.1 Points (nodes)

A point is a geographic phenomenon without a spatial extent, also defined as zero-dimensional (Slocum et al., 2009). However, a point in the shape of a centroid can also represent an entire area. The shape of a point symbol can take a graphic or a mimetic format. In most cases, when displaying movement behaviour, a point symbol will visualise quantitative data. This research also examines a design variant that combines qualitative and quantitative data.

A point symbol can represent one or more values. For example, a bivariate point symbol can visualise the ratio between the number of incoming and outgoing travellers. A multivariate point symbol can show people boarding and alighting at several trajectories per driving direction. Geometrical proportional symbols can consist of multiple elements, as in a point diagram. Multiple attribute values can be displayed by placing symbol elements against each other or partially overlapping (Kraak and Ormeling, 2010).

When visualising transit stops in a network flow map, the nodes should be shown at the stop's exact geographical position in the map (Dent, Torguson and Hodler, 2009). This means that the cartographer is limited in how the symbology is displayed because it would be impossible to free space on a map for other nodes or edges by altering the placement of stops. Alternatively, nodes and edges can be shifted to create space for other elements or when a bus or a tram stop are physically next to each other. The disadvantage of a schematic representation of the network is that the geographical context is missing and the user can get a wrong impression of the distances between the nodes.

Designing and visualising nodes has several drawbacks and limitations when it comes to zooming in and out of an interactive map. When too many map elements are shown in the map in relation to the available space, cluttering occurs, making the symbology, labels, and context of the base map challenging to read (Tyner, 2010).

Depending on the scale of the map and the geographical location, over-plotting of stops may occur (He et al., 2019). Such overlapping of symbols decreases the readability. If all modalities require additional data, such as precipitation at a stop, besides the number of people boarding, there is a risk of symbol overloading (Dent, Torguson and Hodler, 2009).

To prevent over-plotting, Kraak and Ormeling (2010) propose to shift nodes slightly. However, the relationship with the environmental context must be maintained as precise as possible. This prevents a stop from being depicted on the wrong side of a road or a river.

The second solution is the application of transparency in combination with the classification of data. Since (partially) shielded symbols remain visible behind an overlapping symbol, the map reader can explore the data with greater ease (Slocum et al., 2009). There is a limit to the number of superimposed symbols because, at a certain moment, nodes with precisely the same position and size become no longer visible and indistinguishable.

An alternative solution is found in using cut-out circles. Here, the edge or stroke of a node is shown in a different hue regarding to the fill of the node. The deviating colour ensures that overlapping nodes can be distinguished from each other. A disadvantage of this method is that it creates a three-dimensional map image in a two-dimensional context. It takes the map reader more time to distinguish features and assign the correct value to a node (Slocum et al., 2009).
Korpi and Ahonen-Rainio (2013) introduce a set of criteria and cartographic generalisation operators to reduce cluttering of symbols in the map. The aim is to reduce the complexity of the map image and the underlying data while maintaining spatial accuracy. When the user zooms out of the map and symbols are generalised, it should be clear to the map reader that a symbol is composed of several features (Opach et al., 2019), allowing the user to zoom back in again to view details.

An automated script in a GIS can ensure that there is always a minimal buffer between nodes. However, this technique can only be applied to a limited extent for geo-referenced nodes (Nocke et al., 2015).
Other techniques to make hidden symbols visible are interactive lens applications such as fisheye distortion and filtering (Tominski et al., 2017); tool glass widgets and Magic Lens filters (Bier et al., 1993); or 3D panning that allows looking at the map and the displayed symbols from a fresh

perspective. These applications make hidden symbols visible. Zinsmaier et al. (2012) suggest semantic zoom as a solution for visual cluttering. Zoomable user interfaces allow for changes in the type and meaning of information displayed depending on the selected map symbol and zoom level (Modjeska, 1997).

It is important to note that the solution paths described above carry the risk of information loss. The presentation of data in an interactive map is so different that it requires an extra cognitive effort by the user. The data on such a map can only be read correctly by a user if the information is displayed within a certain zoom range. Finally, a solution for visual clutter, occlusion and over-plotting can be implemented in a GIS only to a limited extent (Opach et al., 2019).

2.6.2 Lines (edges)

In this thesis, the terms "line" and "edge" are used interchangeably, although an edge normally gives a direction to the geographical phenomenon.

Edges between nodes are used in this study to visualise the total number of person movements between areas in a particular direction and a specific period. Through line scaling, the width of the edges is determined to express quantitative values. The maximum width is determined by the highest attribute value and the space between the other lines and the displayed nodes. An edge must have a minimum width of 0.1 mm to be visible on a screen (Field, 2018). As previously described for the visual variable "Size" (section 2.5), the minimal readable thickness of an element depends on the characteristics of the display and the user's eyesight.

Usually, a line twice as wide as another line of the same attribute value is to be also visualised twice as large. If these proportions cannot be realised because the difference between the highest and the lowest attribute value is too large and the visualisation space too limited, one can choose to divide the values into classes. Each class is then represented by a line with a fixed width. Another option is to show values below a certain attribute value through a line with a fixed-line width. The higher values are shown with a line thickness based on the ratio to the highest value (Dent, Torguson and Hodler, 2009). If an edge splits between two nodes, the two flows added together should represent the total value of the trunk.

As described in the previous section, attribute data can be expressed not only by line thickness but also by hue. Lighter and darker hues, or more saturated hues, show the difference between low and high values (Jenny et al., 2018). A notable deviation of colour use can be found in online traffic maps, which display congestion in the colours green, orange, and red. When using colour to distinguish between different classes or attribute values, it is essential that the edges with the lowest value are wide enough to keep the colour recognisable (Dent, Torguson and Hodler, 2009). Tobler (1987) holds the opinion that quantitative data can be better represented by the use of line widths, arguing that width is better interpreted by users.

Remarkable in the literature are the different findings regarding straight versus curved edges based on user research. Xu et al. (2012) note that connections between nodes can be recognised more quickly with straight lines and that they reduce reading errors. A notable criticism of this conclusion is that in this study, all edges have the same curvature instead of each curvature being optimised for the space in the map (Jenny et al., 2018). As a result, the options with curved lines appeared more cluttered than the ones with straight edges. In contrast to Xu et al. (2012), Purchase, Cohen and James (1996) conclude that curved edges contribute to better readability. Of the 97 flow maps inventoried by Jenny et al. (2018), 48% used curved edges. Of these flow maps, 77% of the curved edges were symmetrical. When using curved edges, sharp corners should be avoided as they reduce legibility.

Another extensive study of edge design by Holten and van Wijk (2009) has examined the extent to which attribute values can be read correctly as well as the speed of this process. This study concludes that respondents have been able to read the values with the greatest accuracy when using animated dash-pattern textures. Using tapered edges has minimised the time the candidates needed to read the values. A compressed version of animated dash-pattern textures is better suited for correct interpretation only in case of very long edges.

A flow line is divided by Zhao et al. (2018) into a head, body, and tail. They discuss different symbology for each part and provide ideas for cartographers to apply in the visualisation of movement behaviour. In this research, several forms are selected and incorporated in a concept flow map that is tested for readability and usability by public transport experts.

Besides the regular display of edges based on attribute values, Dent, Torguson and Hodler (2009) present three alternative visualisation methods: dot method, rendering parallel lines, and line patterns.

The application of the dot method places per unit, for example, ten passengers, a small dot next to the line, allowing the user to see the differences per route between nodes. The dot method needs less space to show the proportions between routes. It requires a great deal of effort by the cartographer to place the dots in such a way that the user is not confused about which dot belongs to what edge. The body and arrow of the flow line can also be displayed in dots of different sizes that represent not only a direction but also the flow value (Zhao et al., 2018).

Showing multiple uniform parallel lines on one or both sides of the edge requires an available space between the existing edges and nodes. As with the dot method, it is a challenging solution for the cartographer. For the visualisation of movement behaviour, a similar situation arises when several lines are running on a particular route. Although Steiner (2019) does not discuss elaborations of multiple parallel flow lines, his summary of flow line alternatives provides interesting examples that can serve as a basis for multivariate flow lines.

As a third option, Dent, Torguson and Hodler (2009) describe the application of an area pattern on edges to distinguish numerical classes. In this method, dark patterns with less white space represent a class with higher values than a lighter pattern. Alternatively, different colour intensities per class can be used. A unique structure can be used as an option (Zhao et al., 2018).

When creating a flow map, several design rules must be followed. Dent, Torguson and Hodler (2009) recommend placing smaller flows on top of larger ones to enhance the readability of less pronounced flows. It is necessary to select a maximum flow width manually, ensuring that none of them exceeds the length of an edge. The difference between the maximum and the minimum flow width must always be 10% (Stephen and Jenny, 2017). Holten and van Wijk (2009) describe an alternative form to represent the direction of a movement, known as the tapered flow method. They argue that the tapered shape of the edge is more comprehensible than arrowheads. Eye-tracking research conducted by Netzel, Burch and Weiskopf (2014) confirms this finding. However, it is noted that the use of tapered width does not work with longer flows because it takes more time for the user to notice the difference between the thicker and the thinner side of the edge. Research by Jenny et al. (2018) among 215 respondents gives a different picture, concluding that 88% of the respondents have preferred arrows instead of tapered flows.

The second point of the research focus concerns the effect of the attribute value on the thickness of a tapered line (Jenny et al., 2018). In the applications of Holten and van Wijk (2009) and the user research by Netzel, Burch and Weiskopf (2014) only one line width is used. Besides to the flow line components and shapes described above, Zhao et al. (2018) propose design solutions as depicted in figure 3.

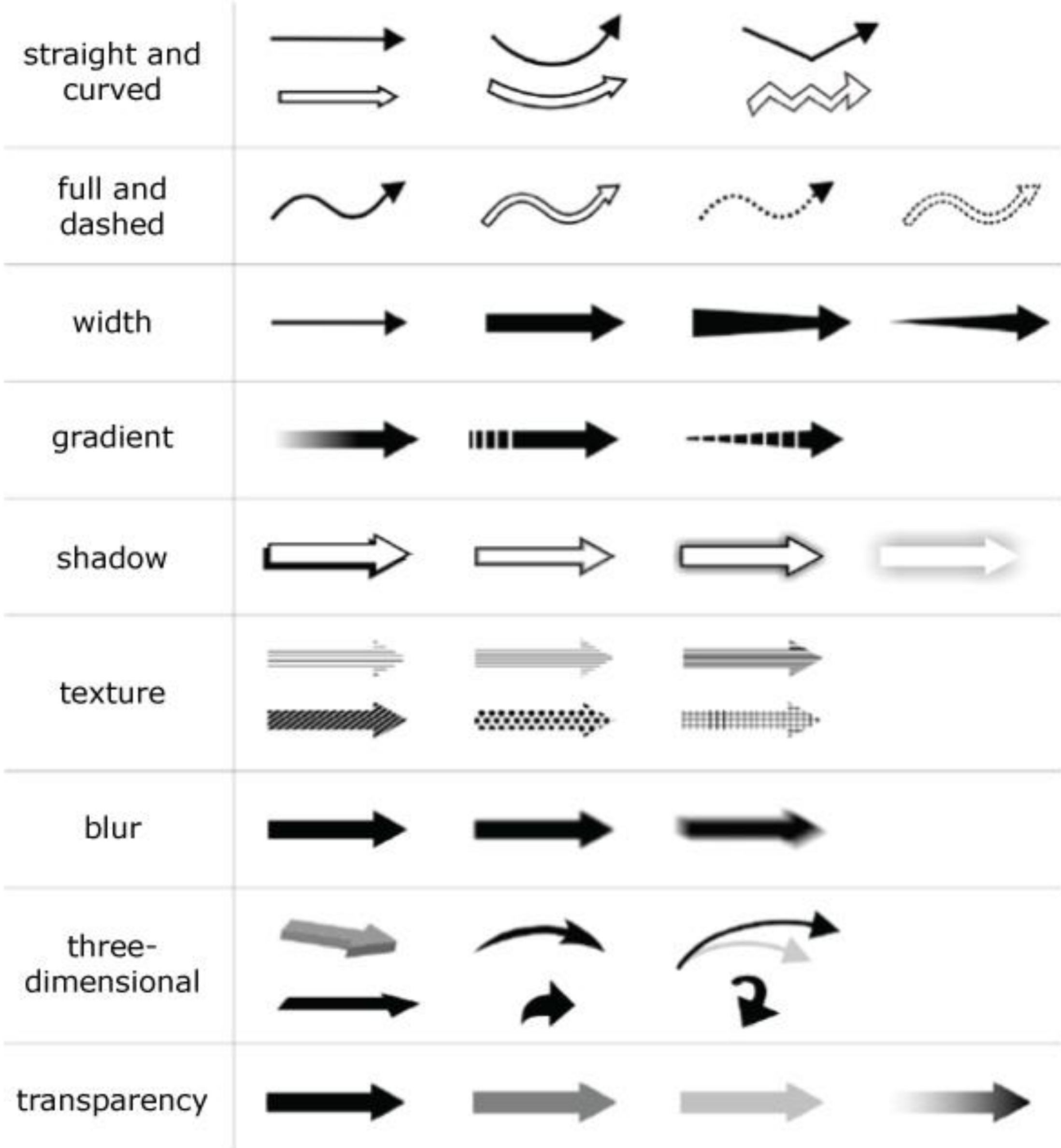


Figure 3: Flow line symbology (Zhao et al., 2018)

Network flow maps often show the total traffic between the two nodes. In order to map the travel behaviour between neighbourhoods or transport hubs, usually, two edges are needed between two nodes for incoming and outgoing travel. Because in the Netherlands, people drive on the right side of the road, it could be concluded which direction a line represents. Using arrow edges or animated flow lines to show the direction requires additional design rules. For arrowheads, these must be scaled proportionally to the line to which they belong.

The perspectives outlined in this section aimed at achieving an effective visualisation of movement behaviour leave sufficient room for discussion. Whether the number of incoming or outgoing persons in an area can best be represented by a proportional point symbol or by a pie diagram, or whether the movement behaviour is best represented by a line thickness or by colour, is further examined in the empirical study.

2.6.3 Summary flow map symbolisation

This chapter discussed the applications of flow map feature types. Two challenges are presented. First, due to many crossing lines between nodes representing neighbourhoods, there is a risk that the flow map becomes unreadable.

For qualitative research, this means that edge and node variants are designed and tested for usability based on tasks (see Appendix C - Flowmap_1, Flowmap_4, Flowmap_6, Flowmap_9, Flowmap_17, Flowmap_19, Flowmap_20, Flowmap_21, Flowmap_36, Flowmap_37, Flowmap_38, Flowmap_39, Flowmap_41, Flowmap_42, Flowmap_43, Flowmap_44, Flowmap_45, Flowmap_46, D1_blue_flow_map and D2_dynamic_flow_map).

A second challenge arises with the excessive linking of external data sources to nodes and edges. The symbology can include multiple components to visualise unique attribute values. This makes it more difficult for the map reader to interpret the flow map correctly.

In the qualitative research, the combination of movement behaviour and external data sources is tested with policy makers (see Appendix C - Flowmap_20 and D2_dynamic_flow_map).

Researchers disagree on which symbolisation can best be applied to represent the edges between nodes. Both straight and curved lines have advantages and disadvantages. Scholars are also divided about what method visualises the attribute value of a line as effectively as possible. One group is of the opinion that line thickness is best suited to visualise a value. Others state that colour is better able to do so.

The two preceding sections described different solutions that allow representing the symbology in a readable and interpretable way. Previous studies only tested design solutions with GIS experts or students. In order to use flow maps as a useful tool in the decision-making process of public transport companies, the actual users need to be involved in the evaluation phase of the user centred design process.

Qualitative research with transport experts should test their performance and reveal their attitude towards flow map variants. Decision-makers will evaluate the most promising design solutions and most discussed visual variables in the literature studied during a usability test. Table 3 summarizes the flow map symbology, map elements and underlying visual variables which are evaluated on effectiveness, usefulness and user reactions (Koua, Maceachren and Kraak, 2006).

Visual representation	Objective	Flow map design variant (Appendix C and D)
Edge - curved versus straight edges	Determine why it takes less time for a transport expert to establish the relationship between two nodes using straight lines or curved lines. Find out why a decision-maker is more likely to see patterns in the map based on straight or curved edges. Identify why a policymaker prefers straight or curved edges.	Flowmap_0, Flowmap_1,
Edge - line thickness versus colour hue	Determine why it takes less time for a decision-maker to detect whether there are more or fewer movements between areas based on line thickness or the colour of a line. Find out whether a policymaker is better able to determine the amount of movement between areas based on the line thickness of an edge or using a line colour. Determine why a transport expert prefers the use of line thicknesses or colour in a flow map to determine the intensity of the movement behaviour.	Flowmap_1, Flowmap_4, Flowmap_9, Flowmap_11, Flowmap_18 and Flowmap_36
Edge - arrowheads	Identify why it takes less effort for a transport expert to determine the direction of an edge depending on the arrowhead variant A or B. Why does a policymaker prefer arrowhead variant A over B or the other way around?	Flowmap_1, Flowmap_4, Flowmap_36, D1_blue_flow_map and D2_dynamic_flow_map
Edge - gradient versus solid fill	Determine why it takes less time for a decision-maker to detect the ratio between incoming and	Flowmap_36

	outgoing travellers for an area observing an edge with a gradient or a solid fill. Find out why a transport expert prefers edges with a gradient or a solid fill.	
Edge - transparency and stroke halo	Determine why it takes less time for a transport manager to establish the relationship between two nodes using transparency and halo or single strokes with 100% opacity. Why does a policymaker prefer transparency and halo over opacity and single strokes or the other way around?	Flowmap_1
Node - circle diagram versus an alternative geometric symbol	Find out why a transport expert needs less time to retrieve the number of incoming and outgoing travellers from a pie chart or alternative point symbol. Find out why a policymaker prefers a circle diagram or an alternative point symbol.	Flowmap_1, Flowmap_6, Flowmap_11, Flowmap_13 and Flowmap_37
Node - proportional circle size versus colour	Find out why a transport expert needs less time to retrieve the number of incoming and outgoing travellers from a node with a proportional size or based on a colour hue. Find out why a decision-maker prefers a proportional circle or node where a colour represents the value.	Flowmap_1, Flowmap_6, Flowmap_11, Flowmap_13 and Flowmap_37
Interactive map - information pop-up versus a legend	Determine why it takes less time for a decision-maker to retrieve information in the flow folder using pop-ups or a legend.	D1_blue_flow_map and D2_dynamic_flow_map

Interactive map versus static map	Identify why it takes less effort for a policymaker to determine the movement between areas from a static or an interactive flow map. Find out why a transport expert prefers a static map or an interactive map.	Flowmap_20, Flowmap_51, D1_blue_flow_map and D2_dynamic_flow_map

Table 3: Overview of flow map symbology variants to be evaluated in the qualitative research phase

Before describing how the flow map variants are tested among transport experts, the following section discusses the factors that influence the visual perception and interpretation of the map reader. A theoretical framework is needed to understand how a policymaker explores geo visualisations and bases decisions on it.

2.7 The effect of flow mapping on a transport expert's cognitive load

This section explains which factors affect a decision-maker's working memory, learning, and information processing when consulting a flow map. For a map designer, this insight is critical to consider when creating a geo visualisation. This section aims to apply definitions of the cognitive load to techniques to measure the usability of suggested geo visualisations.

Visualisation methods that reduce the cognitive load on the map reader do not take as much space in the working memory. This enables the user to apply the newly gained knowledge in more advanced schemata (Paas, Renkl and Sweller, 2003). Further in this section, we will discuss the role schemata play in the cognitive process.

Since a flow map is consulted with a mapping application, the user interface of the used software determines the cognitive load the user experiences to a large extent. However, this thesis focuses on the impact of the visualisation of symbology and map elements on the cognitive load. Mapping functions will only be discussed if they can help reduce the cognitive load of a symbol. For the qualitative research, this means that the usability of map functions such as filtering or clustering will be tested with transport experts (see Appendix C - D1_blue_flow_map and D2_dynamic_flow_map).

Cognitive load shows the demand for working memory to process information. As soon as tasks become more complex, a more significant burden is placed on the working memory. In case of an overload, the ability to process information decreases (Baddeley, 1995, 1999).

Processing the information in a flow map has three different types of cognitive load that affect the working memory, learning, and information processing. Intrinsic cognitive load is related to the complexity of the flow map itself. Its significance is influenced by the extent to which a transport expert has to combine and compare different types of data and sources in order to comprehend information (Zheng, 2009; Ooms, 2012). The impact of complexity of flow maps is investigated in the qualitative research by providing multiple data sources and different map functions (see Appendix C - Flowmap_20, D1_blue_flow_map and D2_dynamic_flow_map).

The second type of cognitive load is extraneous, which occurs because of disruptive factors on or around the computer screen or because of poor design of the flow map elements (Zheng, 2009; Ooms, 2012). It is more challenging to detect edges that have the highest volume of travellers if the lines have similar colours, line thicknesses, or overlap. Overlapping nodes displaying volume of incoming and outgoing travellers are challenging to read as well.

Finally, germane cognitive load is strongly related to the learning process. While acquiring information, the working memory establishes a relationship with previously gained knowledge stored in long-term memory (Harrower, 2007). Flow maps that properly facilitate the transfer of information can make the use of the working memory more efficient. Consulting the schematic knowledge from the long-term memory ensures a significant cognitive load when processing the data from the flow map (Zheng, 2009).

Collected knowledge about an item, situation, or event stored in the long-term memory is called a schema (Matlin, 2005). A schema comprises elements that have a hierarchical classification. Related concepts are linked to other schemata. Their role is to recognise and interpret new experiences and acquired data based on previously stored memories in long-term memory (MacEachren, 1995; Matlin, 2005). Schemas allow a person to predict the outcomes of different scenarios (Matlin, 2005). In the qualitative research, it is worth investigating how a public transport expert can derive new insights regarding movement behaviour between areas based on his own schemata and the visualised data in the flow map (see Appendix C – Flowmap_25).

The schemata related to a spatial theme can be constructed based on two types of knowledge. These schemata are also called cognitive maps or mental maps (Downs and Stea, 1977). The primary knowledge is obtained by physically moving through an area and storing what one sees in their memory. The geographical knowledge of the service area and network of the public transport company is tested during the interviews with transport experts as part of the qualitative research (see Appendix B). This form of acquiring knowledge differs from what the same person gets from looking at a map. The secondary method of knowledge acquisition is based on studying the features on the map. It concerns the characteristics and presentation of the flow map's features on one side and the spatial framework and the relationship between objects on the other side that together form a schema in the long-term memory (Kulhavy and Stock, 1996).

Scientists posit that the long-term memory of expert users contains richer schemas than those of non-experts. Their schemata are better structured and consist of larger chunks of information that can be interchanged with the working memory (Matlin, 2005; Ooms, 2012).

Research shows that inexperienced map readers need more time to detect and interpret a map's features. Measurements show novices make more abnormal eye movements and are more fixated on the elements within the map than experts. This causes a higher cognitive load in inexperienced persons. Since experts need less time to locate and interpret an object on the map, they can also analyse a more substantial area within the same time (Ooms, 2012).

Providing training and real-time support via GIS initially results in an extra cognitive load on the novice map reader. The performance of the cognitive tasks will eventually improve, enhancing the noticing and interpretation of the symbols, patterns, and relationships (Olson, 1979).

When scanning a flow map, experienced users focus on the main structural elements such as main roads, public transport hubs, and rivers to orient themselves and then zoom in on the edges and nodes of the flow map. When creating the flow map, the GIS specialist aims to represent the main structural elements in line with the design known to the users (Ooms, 2012).

The cartographer can use motion as an instrument to make symbols stand out faster, although this method works effectively only if the number of animations remains limited. The difference between the two stages must be significant enough to stand out and be noticed easily. If the number of movements in the map is too large, the cognitive load will increase (Mowafy, Blake and Lappin, 1990).

This user research involving transport experts measures the influence of map design and the candidates' experience on information processing, speed, and accuracy.

Lloyd (1997) describes three different visual search processes that can occur when finding a target in a map. The characteristics of the target, the number of map symbols, and the diversity of map elements determine the search behaviour of the map reader.

When a user analyses a map on which symbols differ in only one visual variable, such as colour, size, shape, or orientation, it is a single-feature search (Lloyd, 1997). It takes the map reader little effort to detect the symbol on the map.

In case the map reader searches for a target between other symbols and distinguishes it based on two or more deviating dimensions, this is referred to as a multiple-feature search (Lloyd, 1997).

When the area to be investigated comprises map elements with two or more deviating visual variables, and the target contains two or more dimensions, it is a conjunctive search (Lloyd, 1997). Distractors make it more difficult for the map reader to detect a specific element because it takes more time for them to determine that they have found the right symbol. If the element is located at the edge of the map, it increases the cognitive load even more.

The size of the map and the distribution of symbols across it determine the number of eye-movement fixations when estimating values and making comparisons (Wood, 1993). If a geo visualisation for the required scale does not fit on the screen at once, the map reader will have to pan and zoom in and out. The potential solutions to this issue might introduce zooming in on a pre-defined value or by offering a search feature.

Besides the map's extent, colours, shades, and shapes of prominent elements in the base map also affect the cognitive load of the map reader (MacEachren, 1982). They may cause optical illusions that are difficult to ignore, causing the map reader to lose control of information processing (Dobson, 1985). For qualitative research, this means that the usability of different base map types is investigated among policymakers (see Appendix C - Flowmap_35).

When the policymaker studies a flow map to gather information, perception plays a significant role. Previously gained knowledge and experience stimulate the senses when collecting and interpreting the displayed information on the map. Empirical research has shown that visual information processing is influenced by bottom-up and top-down processes (Matlin, 2005; Fabrikant, Hespanha and Hegarty, 2010).

The bottom-up encoding mechanism takes place when the receptors (eyes and ears) perceive the stimuli shown on the map. The map reader detects symbols and associates features such as shape or colour to specify an object (Lloyd, 1997). Via the sensory memory, the registered stimuli are passed on to the complex and more advanced stages of the cognitive system: the (visual) working-memory and the long-term memory (Matlin, 2005). In empirical research into how users perceive stimuli, cognitive impairments such as visual and physical impairments and environmental influences must be considered. In the qualitative research, participants with a visual impairment participate to test the impact of different visual variables and symbology.

The knowledge of geographical objects to be investigated is stored in the memory of the map reader. The information processing of, for example, the social demographic properties of a neighbourhood or the characteristics of the trajectory of a bus line are characterised as top-down processing. This requires high-level cognition that enables the policymaker to discover, distinguish, recognise, and interpret symbology, which is necessary for performing tasks (Matlin, 2005).

Cognitive load can be measured by examining specific constructs. The mental load can be determined by analysing the execution of flow map-related tasks. Such an analysis is based on rating scales via self-reports (Krell, 2017) and introspects (Paas, Renkl and Sweller, 2003). For the measurement of mental effort, questionnaires can also be used, supplemented with eye-tracking based on the tasks presented to the participants.

Despite the subjective approach of questionnaires, policymakers can sufficiently indicate to what extent a task was challenging to perform (Gopher and Braune, 1984).

In summary, it can be concluded that the map reader takes more time to detect a target as the number of distractors increases. The transport expert's experience with maps also plays a role in whether he can make quick and accurate decisions based on the information displayed. In addition, colour is the visual variable that is most helpful in distinguishing between symbols. Adding a second variable, such as shape, size and, to a lesser extent, orientation, can enhance this effect. For this study, it means that the qualitative research seeks the most effective application of visual variables and symbology.

Special attention in the qualitative research is paid to the application of these visual variables and how they are interpreted by a policymaker. For example, what influence does the line thickness, colour or orientation of a symbol have on the transport expert's performance or attitude? How non-experts understand flow maps and then base decisions on them is discussed in section 2.8. To measure the impact of visual variables on the cognitive load of a map reader, various methods and instruments are available. These techniques are further discussed in chapter 3: Methodology.

2.8 How non-experts interpret map symbology and base their decision-making on it

GIS, web mapping applications and geographical data have long been the domain of geographers, cartographers, researchers, planners, analysts, and statisticians. Because of the specific knowledge and experience required and the lack of user-friendliness, GIS was only applied by geo specialists. Extensive knowledge of GIS is now no longer necessary for managers to use geographical data in decision-making processes. The increasing number of commercial and open-source mapping applications provide GIS experts with tools to create web-based information products that non-experts can utilise. User-friendliness of a GIS and readability of geo visualisations are the essential conditions for motivating managers to use spatial data and to make the right decisions.

Figure 4 shows the cartographic communication process (Koláčný, 1969; MacEachren, 1995). The model clarifies that a geo specialist perceives only a part of reality and translates it into a geo visualisation using design and symbols. A map reader then deciphers, visualises, and analyses the offered geo visualisation. Non-experts create their own reality and enrich their knowledge. The gap between the perceived spatial reality of a cartographer and the map reader is influenced by factors such as knowledge, experience, psychological processes, tasks to be performed, interests, and objectives. The properties of the visual variables described in section 2.5 also influence the meaning that the map reader assigns to elements in a geo visualisation (Ooms, 2012).

Public transport managers apply GIS to get answers to specific spatial issues. For example, where the network can be optimised to increase customer satisfaction and return on investment. Geo visualisations can also be explored without a pre-defined problem. They then stimulate idea generation, the interaction between decision-makers, and help transport experts to substantiate their decisions (MacEachren, 1995).

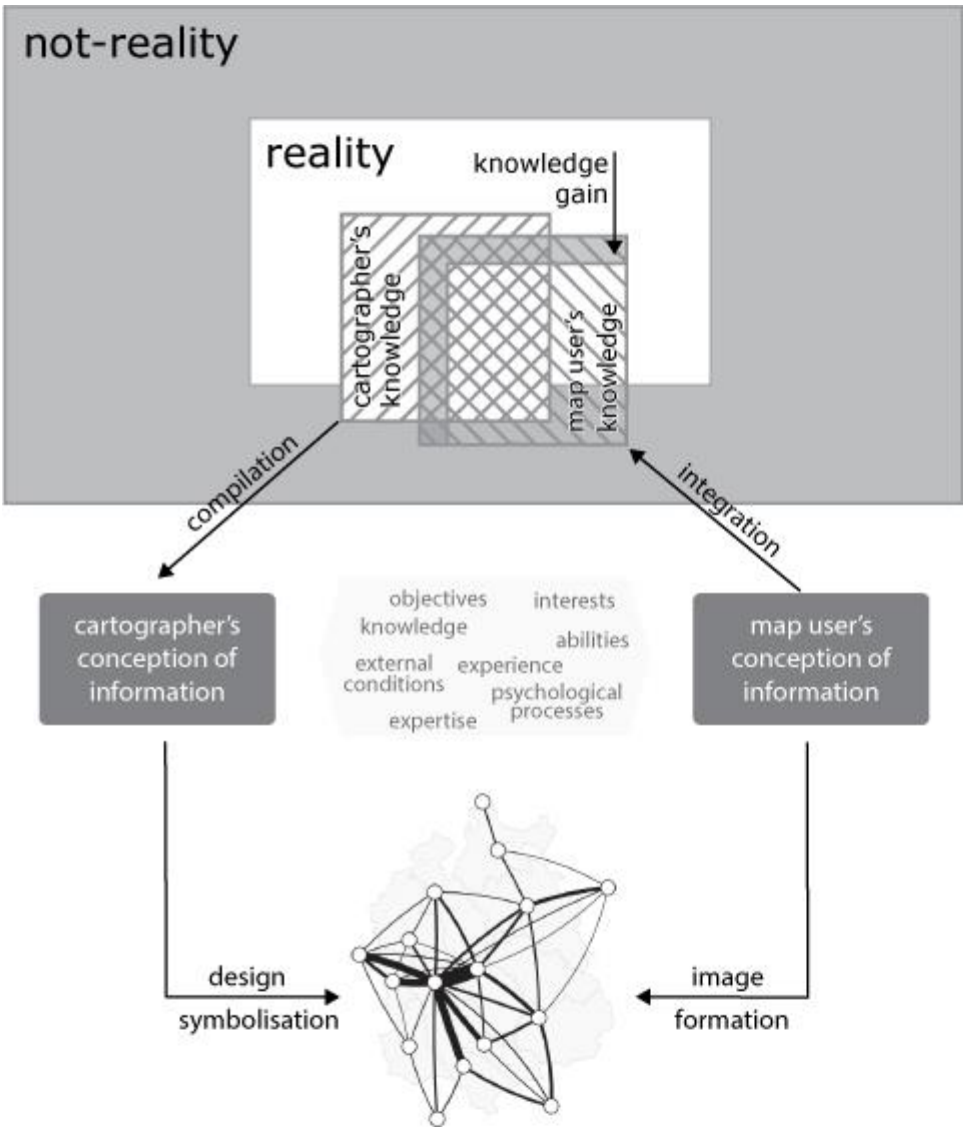


Figure 4: Cartographic communication process (after Koláčný (1969) and MacEachren (1995))

2.8.1 Understanding how transport expert use maps

Children are taught Geography from primary school onwards. Instead of learning toponyms by heart, more and more attention is being paid to identifying geographical phenomena in today's education. This knowledge and experience help to interpret thematic maps at a later age. Buckner and Tulving (1995) speak of "the act of semantic memory" in which prior experience guides the encoding of maps and facilitates the development of strategies for map learning.

This thesis focuses on the use of screen maps, digital mapping that is accessed via a user interface. The usability of the interface determines, to a large extent, to what degree a user can achieve his or her goals while working with a geo visualisation.

Policymakers do not find themselves in a conceptual vacuum when interpreting a geo visualisation (Wood and Fels, 1986). During user surveys, it is valuable to check what geographical and subject-related knowledge a transport expert already has. In addition, it is vital to understand how a public transport manager interprets a map and what tasks he wants to perform to achieve his goal (Kulhavy and Stock, 1996). In the qualitative research, the transport expert is asked to identify promising routes in a flow map (see Appendix D - Flowmap_25).

When effectively consulting a digital map, not only the user-friendliness of a map application plays a role. Environmental variables, computer performance, and the quality of the monitor also influence the experience of the map reader. These aspects are not taken into account in this study.

This section focuses on the observation process and the influence of the vision of a map reader. The eyesight of the map reader is a system of psychophysiological and neurophysiological aspects (Cauvin, Escobar and Serradj, 2013). Sensory stimuli activate the eye of the map reader. Then, the observed image is sent via the optical nerve to the iconic memory.

Based on earlier work by Keates (1996), MacEachren (1995) and Cauvin, Escobar and Serradj (2013) the following phases in the map reading process and the use of the map can be distinguished.

Phase 1 - Defining the issue and purpose

Before a manager commences to consult a geo visualisation, it is necessary to develop a clear understanding of the issue to be solved. What information and insights does the manager need to make the right decision? What tasks does she or he need to complete in order to achieve her or his goal?

For decision-makers in public transport, insights into travel behaviour between neighbourhoods in a specific period are essential to improve the timetable and the network. Such changes should lead to higher customer satisfaction and revenues.

Phase 2 - Spatial data selection

Correct metadata assigned to a map helps the manager to select the correct geo visualisation. Metadata provides an insight into the topicality and source of the data, the geographical area, the scale, the features, and the attribute data in the map.

The applicability of a map is recognised based on these fundamental qualities. Denègre (2005) notes that a geo visualisation must be presented as concisely as possible and that the information displayed must be adequate, accurate, and reliable.

Phase 3 - Perception

There is no unambiguous definition of the term "perception." In map reading, according to Olson (2015), it refers to the first perception of an element on the map or the map as a whole. Each person experiences map elements in their own way. Despite the standardisation of colours in cartography, such as the use of blue for water-bodies or green for nature, the customs and conventions of the map reader will have to be respected. This helps to minimise the effort the user must make to fathom the visualisation. Therefore, the colour schemes used may be at odds with the views of cartographers and the theories of scientific visualisation (Brewer, 1997).

In addition to the aforementioned fundamental aspects that a map must meet, Denègre (2005) also mentions graphical qualities that are related to how the map reader perceives the visualisation.

First, readability determines, to a large extent, to what degree the user can correctly perceive the content. Selectivity also makes it easier to distinguish objects in the map. Finally, aesthetics influence the appeal of viewing and studying the map.

Visual perception can cause a distorted image because colours, shapes, and the size of symbols influence each other. Research should show which symbology reduces the chance of geometric illusions (Cauvin, Escobar and Serradj, 2013).

In addition to the GIS interface, the map reader sees two types of data: features and structural information (Kulhavy and Stock, 1996). Features mean all stimuli that distinguish and interpret specific entities. Structural information provides a framework in which the relationships and relative locations between the features become visible, for example, with the help of edges that connect the nodes in a geo visualisation. Structural information is assigned a more critical role than symbols, scale, or projection in understanding geo visualisations (Castner and Eastman, 1985; Ottosson, 1988). Yet, both features and structural information play an essential role in the way the map users encode and remember elements on a map. Kulhavy and Stock (1996) note that the map as a whole predominantly determines how the information on it is perceived.

Phase 4 - Visual search

Initially, the focus of the user opening a screen map will be at its centre. A highly distinctive symbol can immediately shift the focus to another position on the map. If the node to be examined is far from the centre of the map or even is located outside of the zoom level, this will affect the user's response time (Lloyd, 1997).

Suppose we ask the map reader who has just confirmed that they are looking at the right geographical area about the features that attracted their attention first. In that case, they will answer this question by listing the map elements that pop out of their memory (Lloyd, 1997). Therefore, when designing the map, the cartographer has to determine which features should be most salient. The visual arrangement process helps to make the essential elements more eye-catching (Cauvin, Escobar and Serradj, 2013).

It can also happen that the map reader does not have a specific issue or request. Here, they explore the map to gain knowledge. The distinctive and striking map elements will guide the user's processing of the information.

Information processing is not only done based on what the user sees on the map. The visual system of the map reader also groups, arranges and interprets the features on the map. The eyes of the user send the image of the observed elements to the brain. There, the recognition of previously observed map features occurs. The user can pay attention only to a few elements on the map at the same time. Each of the map symbols calls for attention and evokes associations, depending on the difference in colour, size, shape, and orientation of a symbol.

Motivation and involvement also determine whether the map reader considers a map element important enough to perceive and store in their memory. Symbols stored in the brain are assigned meaning and analysed for distinguishing patterns (Cauvin, Escobar and Serradj, 2013).

With conjunctive search, a public transport manager looks for the relationship between two neighbourhoods. The distance between the nodes, the number of nodes in the vicinity, and whether one or both areas are displayed directly on the screen influences the response time and performance of the policymaker.

According to the Gestalt psychology approach, map users see larger areas with defined shapes and patterns. This implies that the map readers unconsciously try to organise the depicted map elements (Ooms, De Maeyer and Fack, 2014). The concept of grouping represents how people tend to interpret a visual field or issue in a certain way. The primary rules of grouping described by Wertheimer (1923) are based on proximity, similarity, closure, simplicity, continuity, connectedness, figure-ground, familiarity, experience, shape, or common fate.

Geographical knowledge of the research area determines, to a large extent, how much effort a transport expert has to put into distilling information from the map about a route or a stop. Depending on the scale and the cartography, a reference map helps the user to find points of reference via the displayed features. The orientation on the map can be disturbed by unnecessary or unclear map elements that cause visual noise. Tufte (2001) talks about the data-ink ratio when referring to this problem. In this study, this concept refers to the ratio between the total available surface area for presenting data and the flow map. The aim is to distract the map reader as little as possible with irrelevant elements. An alternative method to prevent the overload of the short-term memory capacity of a map reader is to use a maximum information density. Bertin (1983) discusses in his illustrious work "Semiology of Graphics" the use of a maximum of 10 stand-alone graphical or textual elements per cm^2 in the map.

Phase 5 - Tasks

Following the observation and search process described above, a policymaker has to carry out several tasks to gather the knowledge and insights necessary for informing his decisions. Koua, Maceachren and Kraak (2006) designate these tasks as visualisation operators. Based on the complexity of the issue, the tasks can be classified as follows.

Low-level tasks

Detection

It is essential that the map reader can detect the symbols on the map. The previously mentioned minimum size of 0.1 mm (Field, 2018) must be tested per each user. A sign's contrast with the background and surrounding map elements determines the extent to which it is detectable (Jenks and Knos, 1961).

Discrimination

The map reader must be able to distinguish the observed elements from each other based on adequate differences in form, dimension, and contrast between map elements (Keates, 1996). The cartographer must establish the most effective and efficient variety of map elements observable by the map user.

Identification

Before identifying an element in the map, a manager must be able to attribute its existence or meaning to a symbol via the legend or information pop-up. Too insignificant differences between elements (discrimination) can create confusion when identifying signs (Keates, 1996).

Location

To read the data on a line or a node in the map, a transport expert must be able to locate it first. This can be done based on their geographical knowledge, map annotation, or using a search function in the GIS interface.

Clustering

With many similar features that are close together, the map reader can increase the readability by clustering elements. A textual or graphic feature then displays the value or meaning.

Categorising

The map reader can assign the correct classification to the distinct features in the map or read them in the legend. By dividing the features in the map into logical categories, the map reader can filter the information better. Therefore, categorisation increases readability.

Comparing

If the map reader can detect, distinguish, and identify signs, symbols can be compared, providing an insight into which lines represent low or high movement intensities.

Intermediate-level tasks

Ranking

Employ the colour, size, shape, or orientation to rank the edges between stops showing the occupancy rate or ranking the number of boarding or disembarking passengers at a stop. Ranking attempts to organise the observed elements.

Associating

The map reader searches for relationships between two or more objects on the map. The link between the objects is not always obvious. Features that help to build associations are usually not identical (Wehrend, 1993).

High-level tasks

Correlating

The symbology in the map helps a public transport manager to discover connections. Unlike tables of data, a map can show the environmental context that makes it easier to detect unusual or unexpected correlations. Subsequently, a manager can interpret phenomena more quickly and make a more informed decision.

Decision-making

This task is further elaborated on in the following section.

Phase 6 - Decision-making

When deciding, an individual or a group of people collects information during a higher-level cognitive process to solve a problem (Payne, Bettman and Johnson, 1993). Based on the data collected, alternatives are evaluated, and a choice is made (Carroll and Johnson, 1990).

Policy issues related to a timetable and a transport network always have a spatial component. Therefore, spatial insight provides support when making decisions. A digital twin of a city and movement data make it possible to visualise the number of people moving from one part of the city to another in time. Other sources of data, such a social demographic information, can be linked to help explain or predict travel behaviour.

The enormous growth in spatially oriented data and mapping applications requires GIS experts to continue to develop professionally. Up-to-date knowledge is vital for developing applications and information products for decision-makers based on which they can carry out analysis and inform decisions. Four research directions contribute to the effectiveness of geo visualisations in decision-making: information representation, task characteristics, user characteristics, and decision-making performance (Erskine et al., 2013).

With the help of information representation, a decision is made quicker and more accurately if the representation of the problem corresponds to the problem-solving action. Vessey (1991) refers to this phenomenon as the Cognitive Fit Theory. Also, a query interface design provides the decision-maker with tools to better understand the presented spatial data and to make better decisions (Yang et al., 2011). Large amounts of movement data can be delineated by selecting a specific area in the map or by making connections. For the qualitative research, this means that the flow maps studied relate to the Rotterdam region. The flow maps visualise the top 100 largest travel flows in this area.

The previously described tasks play a crucial role in decision-making performance (Erskine et al., 2013). More complex tasks are characterised by the use of multiple information attributes and the evaluation of many alternative scenarios. Complicated tasks cost the decision-maker more time and come at the expense of decision accuracy and efficiency (Mennecke, Crossland and Killingsworth, 2000). Involving multiple specialists in the decision-making process can offer a solution to this problem.

Researchers assume that user characteristics influence decision performance. Knowledge of the environment, sensory disabilities, education, cognitive skills, and self-reliance influence the map reader's ability to interpret and apply a geo visualisation in their decision-making processes (Slocum et al., 2001; Zipf, 2002).

Decision-time, decision-accuracy, and subjective mental workload are used as gauges for decision-performance. According to Jarupathirun and Zahedi (2007), perceived decision efficiency increases decision performance and stimulates the achievement of goals. Using Spatial Decision Support Systems can also contribute to decision quality by increasing user satisfaction. This is achieved through a user-friendly visual query interface (Speier and Morris, 2003) and an intelligible map.

When using geo visualisations in the decision-making process, the policymaker’s three different memory functions are addressed: the sensory (visual or iconic) memory, the working (short-time) memory, and the long-term memory (Keates, 1996). In the sensory memory, the observed image is briefly stored by the senses to be processed by the visual system in the brain. An appealing map image can be stored directly in the long-term memory by the observer.

Observations, temporarily stored in a person's working memory, can be recorded in the long-term memory in case of a revisit and via the learning process. If the objects are stored in the memory in a structured way, they can also be retrieved more easily with a subsequent decision (Matlin, 2005). Based on the insights gained, a cartographer can formulate guidelines for designing effective visualisations that make it easier for novice users to interpret the spatial data (MacEachren, 1995).

It can be concluded from this section that GIS experts have tools and data at their disposal that enable policymakers to perform effective decision-making based on geo visualisations. Also, the cartographic communication process model reveals that there is a gap between the perceived spatial reality of a GIS expert and the map user. The qualitative research is task-driven. This offers the GIS expert insight into the purpose, knowledge and experience with which a non-expert applies a flow map in the decision-making process.

Visualisation operator	Operational user task	Flow map design variant (Appendix C and D)
Locate	Click on a symbol with a certain value.	Flowmap_6
Identify	Identify the relationship between areas.	Flowmap_21
Distinguish	Distinguish movement flows between two nodes.	Flowmap_3
Rank	Identify the three largest movement flows and the three smallest flows.	Flowmap_1 and Flowmap_2
Compare	Compare movement flows at different locations and the order of volume accordingly.	Flowmap_17
Associate	Identify relationships between incoming and outgoing movement flows.	Flowmap_10
Correlate	Detect relationships between incoming or outgoing flows and attributes of an area.	Flowmap_20
Decision-making	Increase or decrease the frequency of buses per hour between areas based on flow map data.	Flowmap_25

Table 4: List of user tasks derived from visualisation operators applicable in qualitative research

Table 4 lists the selected visualisation operators that have been translated to operational user tasks. Next, tasks will be decomposed in specific sub-tasks for the usability test to identify and analyse the way transport experts explore, evaluate and interpret flow maps. Section 3.4 - Data collection explains the sub-tasks per research method. The complete sets of sub-tasks can be found in Appendix B, C. en D.

2.9 Conclusion

Based on the literature review carried out, it can be concluded that, to date, little attention has been paid to how policymakers and transport experts use and interpret flow maps. Most researchers only involve geo specialists or students in the assessment of flow maps. This gap will be bridged by the qualitative research focusing entirely on the target group: transport experts.

From the literature studied, it is clear that the visualisation of large amounts of movement data poses challenges. The most important issues are poor legibility of the flow map and symbology due to cluttering and occlusion. Second, salience bias and information overload result in distraction and force the map reader to make an extra mental effort.

This means for qualitative research that the flow map symbology should be examined in order to mitigate these issues. The literature lacks specific explanations and solutions for the public transport sector. Through task-driven usability testing, the factors that improve the readability of flow map symbology for transport experts should be improved and clutter and occlusion in the flow map should be reduced.

The literature study provides partial answers to the primary research question by looking at the possible manifestations of flow maps, the symbology to be used, and the impact on the policymaker's performance. It is striking that there are differences of opinion between researchers about the application of visual variables. The differences of opinion range from visualising movement behaviour through straight or curved edges to the use of line thicknesses or colour values.

In any case, it can be concluded that location, size and colour value are the most suitable visual variables to display movement behaviour in static flow maps. Combining visual variables makes it easier for the map reader to derive information and base decisions on it. The different views have been taken as a starting point for formulating user tasks for the usability study. In order to answer the research question.

Interactive flow maps provide functions to display movement over time on a dynamic map. Clutter and occlusion of symbols and map elements are reduced by filtering or aggregating data. This results in a clear flow map, but requires an extra effort from the map reader to make information visible. Scholars disagree about the advantages and disadvantages of interactive flow maps compared to static variants. Both variants are tested in the qualitative research.

The complexity of the flow map, the design, disruptive factors and the spatial knowledge and experience largely determine the cognitive load on the map reader. It is up to the geo specialist to adjust the flow map symbology to the target group.

In order to understand how a transport expert uses and interprets a map, it is important to know for what purpose he does this and what related knowledge he already possesses. Various factors play a role in determining the effectiveness of a flow map. In addition, the map reading process is strongly influenced by the discernment of the map reader, the readability and aesthetics of the flow map. Although that a geo specialist follows the design rules of cartography, this does not result in optimal use by the target group. That is why research into the customs, norms and values of the map reader is essential. It provides insights with which the cartographer be able to create a flow map that meets the user's expectations and needs. Chapter 3 describes the methodology by which this insight can be gained.

3 Methodology

The literature review in chapter 2 describes the directions and the principles for the design of usable flow maps to visualise movement behaviour.

However, the literature studied does not provide sufficient insights into how policymakers apply flow maps when making decisions that improve the accessibility of an urban region. It is also not clear which symbology and design of a flow map offer the most effective and efficient solution.

This chapter describes the research strategy followed to arrive at this insight. First, the choice of research methods is explained. Next, the selection of the test candidates is described. The subsequent subsection explains the flow map variants studied, and the tools used. The method of data collection deals with the steps that are followed to collect insights per research method. Finally, it explains how the collected data is analysed.

3.1 Research design

In this thesis, qualitative research was chosen to answer the research question. First, the number of transport experts specialised in public transport in the Netherlands is too limited to carry out large-scale quantitative research. Second, qualitative research provides detailed insights into the cognitive process of the map reader (Nielsen, 1994).

The qualitative research consisted of three phases: an interview, a usability test, and a post-test questionnaire. The motivation for the choice of the three methods is explained in the sections below.

Because the research took place during the lockdown due to COVID-19, the three phases of the qualitative research were conducted online one on one. Both the interviewer as the participants were at home. Each research session lasted between two and two-and-a-half hours with brief breaks between the three different phases. The online interaction between the researcher and participant provided the opportunity to ask follow-up questions to clarify an opinion, thought, or action taken by the candidate.

Because only 13 people were surveyed, it is not possible to demonstrate a fully representative correlation between a design variant of a flow map and its effectiveness, efficiency and user satisfaction (Clifford et al., 2016). In addition, encoding behaviour and the answers collected during an interview are complicated and time-consuming (Montello and Sutton, 2013).

3.1.1 Data collection

Policymakers and transport experts from the RET, the municipality of Rotterdam and the Metropolitan Region Rotterdam Den Haag were invited for this research. Three weeks before the start of the interview, candidates received an e-mail with the explanation and purpose of the qualitative research. Of the 16 persons written to 13 accepted the invitation. Three days before each research session, participants received an e-mail with a link to the Microsoft Teams environment for the user research, a document describing a scenario for the usability test (see Appendix A) and a consent form for participation in the research (see Appendix H).

At the beginning of each online session, each participant was asked for permission to record the survey. The research design and phases were explained to the candidates. Participants were encouraged to think out loud and to speak freely about their findings.

3.1.2 Interview

During the first part of the interview each participant was asked to locate and mark a set of municipalities, neighbourhoods, public transport hubs and a metro line on a digital base map. In addition, the participants were asked to draw the largest traffic flows in the Rotterdam region on the map. The exact description of the assignments is detailed in Appendix B. The assignments were aimed at determining each participant's geographical knowledge and knowledge of the public transport network. Huynh and Doherty (2007) describe sketch maps as "the extraction of information from a mental map through drawing".

The second part of the interview focused on identifying the current way in which policymakers collect information and how decisions are made based on a proposed scenario.

The average duration of an interview was about 30 minutes. The outcome of the interviews helped to explain the behaviour and performance of participants regarding the assessment of flow map variants during the usability test (Rubin and Chisnell, 2008).

3.1.3 Usability test

In the second phase of the user research, each participant was subjected to a usability test. Usability is the extent to which a system can be used by specified users to achieve defined goals with effectiveness, efficiency, and satisfaction (ISO 9241-11: Ergonomic requirements for office work with visual display terminals (VDTs): Part 11: Guidance on usability., 1998). Researchers also add indicators such as error tolerance, ease to learn (Albers and Quesenberry, 2003), ease of remembering and ease of use (Gould and Lewis, 1983).

Usability testing offers the possibility to investigate the different responses of real users while carrying out a set of tasks. The test candidate performs the assignments in controlled settings and with manipulated variables (Kulyk et al., 2007). This is not only about what the map readers look at but also how they look at the flow map symbols and interpret them.

To the best of the researcher's knowledge, there are no examples in the literature describing the viewing behaviour of public transport experts and their decision-making processes based on flow maps. This empirical research contributes to the theory that helps GIS experts to apply symbology more effectively and efficiently in flow maps for the benefit of decision-making processes by policymakers.

Usability testing also has several disadvantages and limitations. First, learning effects may occur with test candidates during the research. This has been be prevented by changing the source data during the assignments and using different visualisations per task.

Another disadvantage of usability research is that the situation created in the laboratory setting does not fully correspond to the natural environment of the map reader (Rubin and Chisnell, 2008). This has been partly avoided by having the user research take place at a suitable site within the respondent's home environment. Participants have become accustomed to the home office set up during the COVID-19 lockdown period.

Finally, external influences such as sound, light or interruptions can disrupt the testing process. During an online usability test, these factors are difficult to exclude.

Both static and dynamic flow maps were subjected to the usability test. The flow map variants that have been tested in this study are described in Appendix F. The effectiveness and efficiency of the flow map symbology and the performance of a participant have been assessed based on the assignments as described in Appendix C.

Tp prepare for the usability test, each test candidate was asked to read the document "Usability testing scenario" (see Appendix A). The aim of this was to provide sufficient context for the participants to understand the application of flow maps and to reduce possible biases regarding to movement behaviour. The usability test is available online at http://www.ret.nl/onderzoek.

Because it is difficult to read nonverbal behaviour during an online usability test, it is essential that the participant thinks out loud and clearly expresses their feelings, thoughts and opinions. The think-aloud protocol is discussed in the next section.

Think-aloud protocol

During a think-aloud session or verbal protocol analysis, the respondent is encouraged to express their thoughts, experiences, and feelings towards the displayed visualisation and interface when performing a task. This gives the test moderator a better understanding of why a respondent shows a certain behaviour and makes specific choices. It helps the test candidate to express what they think of the depicted symbology directly and to share ideas on solving obstacles or shortcomings. This prevents the respondent from the inability to reproduce their thoughts about a certain situation or visualisation after the completion of the session (Rubin and Chisnell, 2008). According to Rubin and Chisnell (2008), thinking aloud leads to better focus and higher concentration in the participant. It sheds light on misconceptions and confusion and prevents them from being attributed to incorrect behaviour.

Rubin and Chisnell (2008) also mention several disadvantages of verbal protocol analysis. First, they hold the opinion that thinking slows down the thought process. Putting more thoughts into the process of solving tasks, participants avoid making mistakes that would inevitably occur in the real-life setting. It also enables the respondent to correct themselves. For a test candidate, carrying out an assignment and sharing thoughts and experience at the same time is more tiring than in the professional setting. Rubin and Chisnell (2008) also notice that some participants are distracted by speaking during the execution of a task. Other respondents find it difficult to express themselves adequately (Haniff and Baber, 2003). Guan et al. (2006) also criticise the method because they feel that the participants only pretend that they think about solving tasks have, while they actually think about something else, and their eye movements over the map reveal aberrant behaviour.

3.1.4 Post-test questionnaire

During the last phase of the user research, the post-test questionnaire offered the researcher the opportunity to ask about the strengths and weaknesses of the different flow map symbology variants. Participants were encouraged to elaborate on their preferences for a particular visualisation form.

Finally, the participant was asked to fill in personal information relating to his job title, age, educational background and years of experience in public transport. The complete post-test questionnaire protocol is available in Appendix D.

3.2 Participants

A user-centred evaluation ultimately revolves around the feedback from the user of the geo visualisation. Many usability studies carried out in the scientific world use students. Since this research investigates the application of flow map symbology in public transport, the background and experience of the test candidates are essential. Only transport experts and policymakers have been taken part in this user research. Each participant has his or her speed of action, vision, spatial knowledge, and experience of the research area. That is why the study not only looks at the performance between the test candidates but also at the impact of the design variants per respondent.

There are different opinions about the minimum number of respondents for a usability test. Jakob Nielsen (2010) believes that five test candidates with a similar background are sufficient to identify the most important issues in a design. In previously conducted usability studies in the visualisation domain, at least 10 or 12 participants have been retained (Forsell and Cooper, 2014). Rubin and Chisnell (2008) apply a minimum threshold of eight test candidates. In the usability study for this research, a total of 13 respondents were surveyed. Two trainee students acted as test subjects to fine-tune the user research. The profile of all 13 participants is listed in Appendix G.

Despite the small number of test candidates and thus the reduced statistical power, the study provides interesting insights that can be used as the basis for a qualitative study among transport experts worldwide.

3.3 Geo visualisations and equipment

Based on the literature review on the usability of flow map symbology, six edge and four node variants were designed and assessed. The theory's discussion of straight and curved edges and the representation of movement data by means of edge colour or line thickness has been translated into the flow map design variants for the qualitative research (see Appendix F). For the visualisation issues mentioned in Table 1 a possible symbology variant has been designed to improve legibility or reduce cluttering and occlusion (see Appendix C - D1_blue_flow_map and D2_dynamic_flow_map). At the same time, design solutions have been chosen that contain a certain degree of complexity (see Appendix C - Flowmap_11, Flowmap_13 and Flowmap_20). The choice was made to test innovative symbology variants for their usability with experienced transport experts.

Because geographical data is increasingly accessed via an interface and interactive functions make it possible to provide insight into large quantities of data, two dynamic flow map variants were also presented to the respondents. The design variations and the design rationale behind them are described in section 3.3.1.

In order to carry out the empirical research, software, hardware and drawing tools were used. The equipment is discussed in section 3.3.2.

3.3.1 Geo visualisations

The interviews have has been conducted using an online base map created in ArcGIS Online. A web map was used to determine the geospatial knowledge and the knowledge of the public transport network of the RET of the candidates. The extent of the map had a focus on the service area of the RET on a scale of 1:100.000 and contains urban areas, water bodies, railways and roads. Only labels of streets and motorways have been depicted on a larger scale (see Appendix E).

The flow map variants tested in the empirical study were developed based on the discussions and findings in previous studies, as described in the literature review. The symbology was designed based on the map design guidelines, as proposed by Brewer (2005) and Field (2018).

The flow maps were created using the software applications ArcGIS Pro 2.6.2 and Adobe Illustrator 2021. The dynamic flow maps are based on WebGL frameworks, JavaScript and the libraries D3.js and jQuery. All visualisations, questions and assignments used during the interview, the usability test and the post-test questionnaire were presented to the participant through a website built in html.

The designed flow maps are based on the one hundred largest movement flows between neighbourhoods within Rotterdam's ring road on a single day in 2019. The flow map variants are described in Appendix F.

3.3.2 Equipment and software

Participants used their own laptop (Lenovo T480 with a 14" screen or Lenovo T580 with a 15" screen). The interviewer used a Asus ZenBook with a 15" screen. Each session took place via Microsoft Teams. Each participant shared his or her screen and webcam image. The actions on the screen, the webcam image and the sound were recorded with the consent of all participants.

The recordings were transcribed in Microsoft Word and summarised in Microsoft Excel.

The MAXQDA Analytics Pro 2020 software package has been used to code the comments, answers, non-verbal behaviour and the use of design stimuli.

3.4 Data analysis

The comments made by the participants during the three parts of the qualitative research were recorded, listened to and transcribed. After the recording was transcribed for each participant, the text was imported into a software application for qualitative data analysis (MAXQDA Analytics Pro). The recording was listened to and viewed again for each participant. The transcribed text was improved and where necessary the text was supplemented with memos in which the research context and the observed behaviour of the participant per question or task was recorded.

Using open coding, all texts were labelled in MAXQDA. The labels were then grouped into themes. For each theme, an analysis was made of how often an answer was given, which ideas and concepts the participant came up with, which response patterns could be recognised and whether the answers coincided with the insights gained in the literature study.

During the interview, the participant's geographical knowledge of RET's service area and the knowledge of the public transport network were assessed. For every correctly delineated area, location or line, the participant scored one point. Participants could score a maximum of four points for geographical knowledge and a maximum of three points for knowledge of the public transport network. Three levels per knowledge area were determined to rank the spatial knowledge of a participant:

Geographical knowledge level of RET's service area
1) Low level of spatial knowledge - the participant scored a maximum of one point.
2) Average level of spatial knowledge - the participant scored two or three points.
3) High spatial knowledge level - the participant scored four points.

Level of knowledge of public transport network
1) Low level of spatial knowledge - the participant scored a maximum of one point.
2) Average level of spatial knowledge - the participant scored two points.
3) High level of spatial knowledge - the participant scored three points.

The scores have been linked per respondent to the results of the usability test and the post-questionnaire. Correlation is discussed in chapter 4, Results.

When analysing the results of the first phase of the interview, knowledge of the public transport network and the participant's geographical knowledge were not the only considerations. Observations were also made on how participants oriented themselves on a map. In-depth questions were asked about which information, elements and functions should be part of the map in order to quickly and efficiently find a neighbourhood, public transport hub or transport line. By comparing the respondents' behaviour and input, a minimum set of map elements for a base map could be determined which would help the user analyse movement behaviour in a flow map.

After the participant had drawn the requested locations, the test candidate was asked to show the most important travel flows within the Rotterdam region on a regular working day. The purpose of this task was to determine whether the knowledge and thoughts of the transport expert corresponded to reality. In addition, the beliefs revealed whether a respondent thought beyond travel modes or only focused on travel by car, public transport or bicycle. Insight in the mindset of the transport expert is important because it influenced the amount and variety of travel data to be presented. It also helped to explain why respondents look at the flow maps in a certain way during the usability test.

As a last element in the interview, a mobility assignment was presented to the transport expert. The participant was asked to describe the steps in the decision-making process when open up a new housing development to an existing metro line. By analysing the methodology of the participants, it was possible to determine which level of detail and which map elements are essential for optimal decision-making. The influence of both factors on the usability of flow maps was tested in more depth during the subsequent phase of empirical research.

The analysis of how the participant performed the usability tasks helped to understand how map readers used the visualisations and what problems they encountered (Cooper et al., 2014).

The analysis of the responses measured how much time and effort it took the respondent to identify the correct edge or node. The ability of the visual representation to achieve the related objective was also measured. The usability of the flow map symbology was not only assessed in terms of the shape, size, thickness or colour of an edge or node. The questions and tasks also focused on the influence of aspects such as scale level, the function of the legend and zoom, filter and clustering functions. After performing a task, the respondent was asked why she or he displayed a particular behaviour or had a specific opinion about the flow map symbology displayed. The recordings of the usability test were transcribed and coded just like the interviews. The codings were supplemented with information about the individual's behaviour and with information about factors that influenced the performance of the task.

In the coded transcripts, strong similarities and significant deviations between the findings of the participants were identified. The analysis of these findings focused specifically on the following themes:

- The variables and the definition of the quantities that transport experts use when analysing movement behaviour;
- The influence of the environmental context and visual limitations of the respondent on the visualisation and use of flow map symbology;
- The influence of the visual variables and visualisation methods on the usability of flow map symbology and on the mental effort of the map reader;
- The information needs and the desired level of detail of transport experts;
- The way a policymaker uses static and dynamic flow maps and map functions during a decision-making process.

Before any conclusions could be drawn based on the user performance during the usability test, the preferences and arguments of the participants were questioned through a post-test questionnaire. In the analysis of the results of the post-test questionnaire, it was checked whether the answers of the test candidate corresponded to their achievements and the behaviour shown.

4 Results

This section presents all the findings from the interviews, the usability tests and the post-questionnaires. First, it explains the information and level-of-detail transport experts use, to make decisions to improve public transport. Next, the feedback on the different flow map visualisation variations is discussed. The mental effort of the respondents in applying the different flow map variants to their decision-making process is then discussed. In the subsection "Static flow maps versus dynamic flow maps" the preferences of the participants are presented. Finally, the relation between geographical knowledge and knowledge of the public transport network and the performance of the participants is established.

4.1 Information needs, definitions and desired level-of-detail

Participants show they are most familiar with the geography of the areas where they live, work, recreate, or travel. For the areas they know less about, they need landmarks and labels on the base map to orientate themselves. Participants mention the ring road of Rotterdam, the Nieuwe Maas river, the Kralingse Plas, the bridges and tunnels in the city, train and metro stations, Ahoy Events Centre and the Feyenoord stadium as important landmarks.

Participants not only want insight into the differences between travel flows by car, bicycle and public transport, but also to see the subdivision of travel in the flow map by bus, tram and metro. In the visualisation of the edges between origin and destination, transport experts need additional information:

- numbers of passengers,
- the travelling time per modality,
- the travel distance between the potential routes,
- the time of travel movement (morning, off-peak and evening rush hour),
- the average vehicle intensity versus the capacity,
- accessibility of a destination with a specific modality.

To optimise the public transport network, policymakers want to see the area information below in layers on the map:

- the current public transport network,
- the road network,
- the maximum speed per track or road section,
- population density,
- the number of jobs,
- the planned infrastructure,
- the most important destination locations.

Besides the information about the total number of incoming and outgoing travellers in an area displayed through a node, the participants wish to call up more detailed information at the bus stop level or for popular destinations. The information need then focuses on the potential number of public transport passengers within a certain distance around the stop. The transport expert wants to know whether a location mainly produces travellers, like a residential area, or attracts them, like a football stadium.

If the transport expert wants to see more detailed information on the flow map, it should leave information that is not used or has no value out. Participants give the example that streets where no buses can drive should not be on the map. Depicting buildings would then suffice.

Public transport experts responsible for the bus network look in more detail at the geography of an area than a transport developer for the metro network, because here the stations are further apart. The operating area of a metro station is larger than that of a bus stop. A mobility expert from the municipality with a focus on the road network mainly concentrates on the car as modality. The different focus areas and modalities require different levels of detail in which the movement data is presented in the flow map.

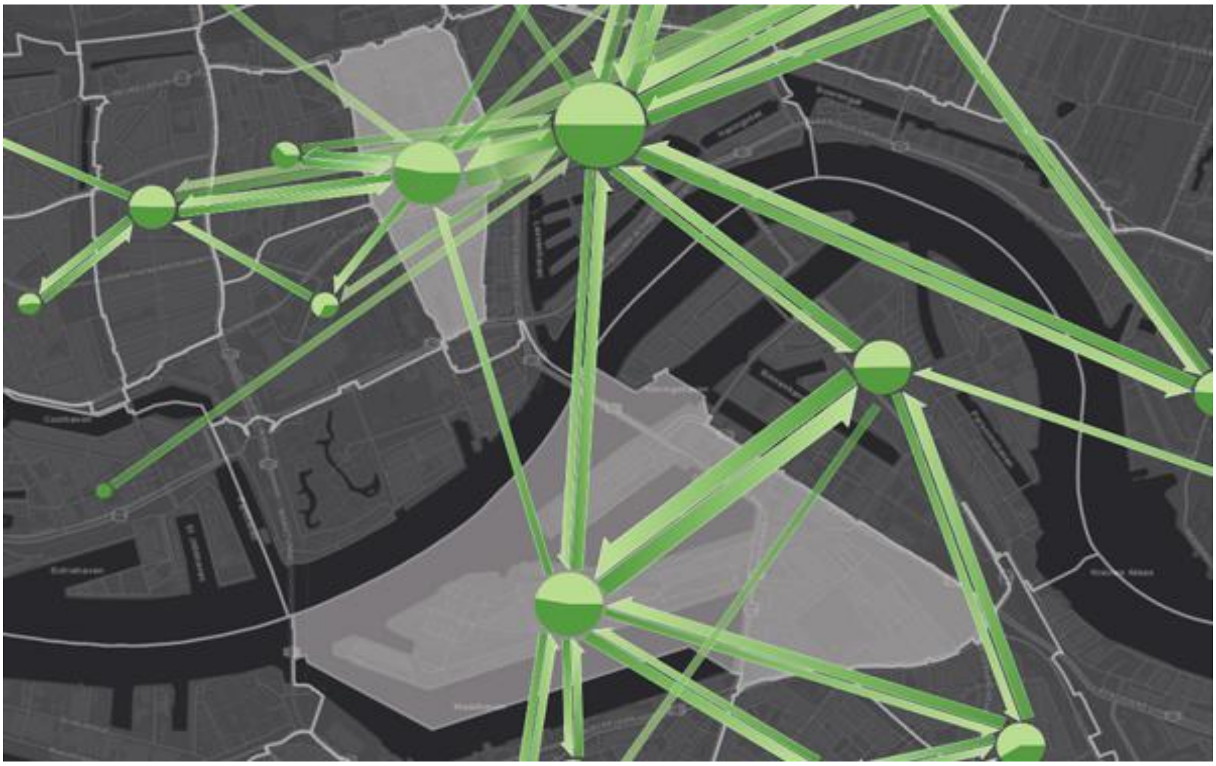


Figure 5: Differences in shape and size of origin and destination areas and the impact on the position of the node

An interesting insight from the usability test concerns the demarcation of the areas between which traveller flows take place. Participants showed that if the areas are too large and the passenger flows are bundled, it is not possible to determine how the movement relates to the public transport network (see figure 5). Respondents note that they have difficulty with the difference in size between origin and destination areas and the shape of the areas. Physical barriers such as a river or a harbour make it difficult to perceive an area as a whole and to interpret travel behaviour.

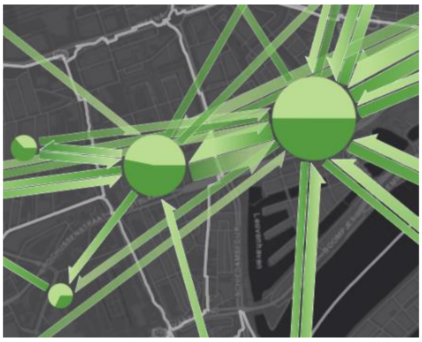
4.2 Observations and interpretation of flow map symbology

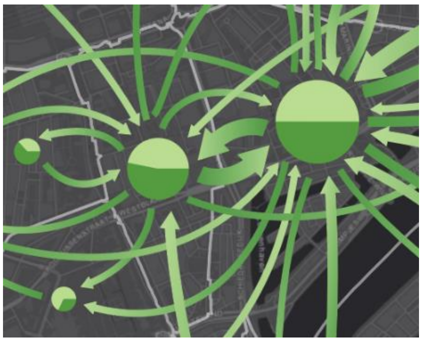
Initially, the participants use the overview maps with main flows between neighbourhoods to identify which areas are interesting to investigate further. The map readers work from large (overview map) to small (detail map). They first scan the overview map and try to discover patterns and structures that stand out or differ because of the thickness or colouring of the edge or the size, or shape of a node. The differences in shape, size or colour should be large enough to be discernible. This is discussed in more detail later in this section.

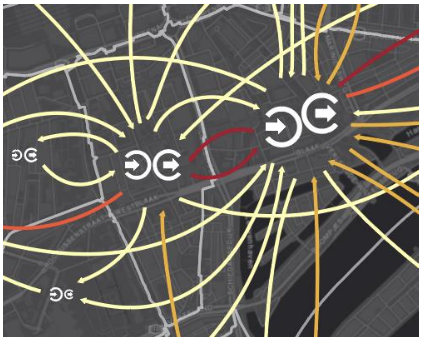
Because transport experts are busy analysing and optimising the network each day, they have formed a mental map of the city in their minds. This has created their own truth about how and where people move through a region. The field of interest of a transport expert also coloured this "truth". There can be a big difference in travel time and distance to be covered between an origin and destination location depending on whether a traveller is travelling by car or public transport.

During the usability test, flow maps were presented that contained a combination of edges and nodes. When carrying out tasks that were specifically aimed at one area (Appendix C task Flowmap_10), confusion arose among the participants which symbols could best be used when solving the problem. Although the answer could be deduced from a displayed node, the attention of participants was drawn to the edges present.

Based on the literature review, six different edge variants and four different node variants were designed and tested for usability. The description of the design elements for each edge or node can be found in Appendix F. The findings from the usability test and the preferences from the post-questionnaire are summarised in the table below.

Edge visualisation	Insights
 **Straight edge with gradient colour fill and half arrowhead** User rating attractiveness: Very attractive 2 Attractive 3 Neutral 0 Unattractive 3 Very unattractive 4 Two participants find this flow map edge layout the clearest and most applicable.	Participants can clearly distinguish between the major flows and the direction. In the areas where many edges overlap, the flow map is experienced as chaotic and participants can no longer read the values. Participants found the arrows revealed the direction of a flow. If several arrows overlap, edges merge into an unreadable knot, despite the white halo around the edges. One participant noticed applied transparency in overlapping edges. Test candidates do not immediately see the application and the relationship with the node based on the colour gradient in the edge from dark green (outgoing) to light green (incoming). It creates confusion among the participants and raises questions. Although all participants agreed that the colour contrast of the edges compared to the dark grey base map was good, they suggested using a different colour to avoid confusion with the colours in the node.

	Most participants had some difficulty in distinguishing the four distinct classes in the edges. They considered the difference in line width between the classes too small. It takes a lot of effort and time for the participants to notice differences between two periods. They think that the line width says too little about the actual size of the movement flow. Participants would like to see the values as a label at the edge. As an alternative, they proposed a filter or selection function that highlights an edge with a certain value in the flow map.
 **Curved edges with gradient colour fill and whole arrowhead** User rating attractiveness: Very attractive 0 Attractive 2 Neutral 6 Unattractive 4 Very unattractive 0 None of the participants finds this flow map edge layout the most clear and applicable.	Participants note that they clearly see the relationship between an origin and destination because edges at most cross but do not overlap. Although the number of edges is the same, participants feel they observe many more edges in the flow map. As a result, map readers feel overwhelmed by the large number of edges in areas where many people move in and out. Participants find it difficult to determine the thickness and classification of the edges because of the curvature of the lines. It also takes them longer on average to perform similar tasks compared to the straight variant. Test candidates think there is a difference between the curved edges that show the flow in and out as an oval and the edges that are shown parallel to each other. The first variant evokes the image among OV transport experts that the outward route differs from the return route. This confusion does not arise in the parallel variant. However, for some participants, the outward and inward directions merge in this last variant, which makes it seem like a much thicker edge and therefore represents a larger flow than is actually the case. Participants do not immediately see the application of the gradient in the edge. Several participants expressed a preference for coloured edges to visualise the distinction between classes.

<table>
<tr>
<td>
Curved edges with four hues and whole arrowhead

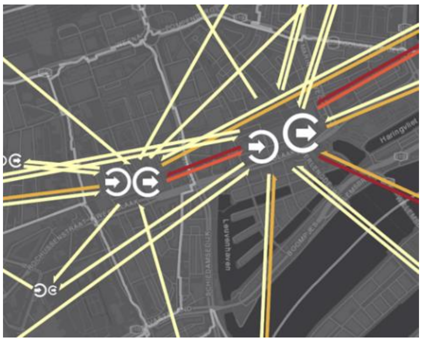
User rating attractiveness:

Very attractive 0
Attractive 5
Neutral 2
Unattractive 5
Very unattractive 0

Three participants find this flow map edge layout the clearest and most applicable.</td>
<td>Participants with normal eyesight can quickly and correctly distinguish the different colour variants and place them in the correct order in terms of value. Even without a legend, they realise light line colours represent a lower value than a darker one. Based on the line colour, respondents could identify differences in value between two points in time more quickly than with the help of line thickness.

By using hues, the edges could suffice with one line width, which meant that respondents found the flow map to be more manageable than the flow maps with varying line widths.

Participants with impaired vision had difficulty distinguishing between coloured edges and intuitively assigning a sequence of values. They mention that they constantly have to make use of the legend. Participants who are colour blind also only see an edge with a dark red line colour after it has been pointed out to them.

Because of the dark grey base map, participants with good eyesight also note that dark red offers too little contrast and it takes more effort to notice the edge. As a second improvement, one participant remarked that the arrow in the edge should be larger.</td>
</tr>
<tr>
<td>
Straight edges with four hues and whole arrowhead

User rating attractiveness:

Very attractive 1
Attractive 7
Neutral 2
Unattractive 1
Very unattractive 1

Four participants find this flow map edge layout the clearest and most applicable.</td>
<td>Participants find the edges with straight lines and a colour per class more readable than the curved variant and edges that show the values with a thickness. A greater difference between the line colours facilitates the interpretation and ranking of values. In the areas where many movements take place, respondents can see which areas are connected. Participants with a visual impairment have difficulty in distinguishing the different hues.

Respondents quickly understand the difference between high and low values without a legend. Differences in values between two time periods are quickly perceived.

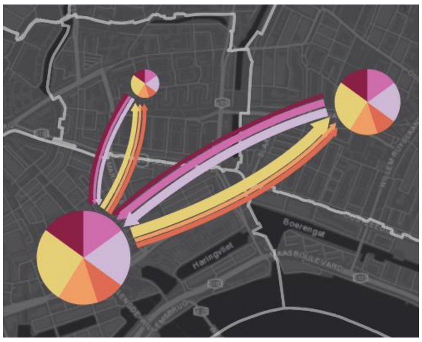
Participants noted that there was room in the flow map to increase the width of the edges and the space between them. According to the participants, this improves readability. If the outward and return directions have the same colour, two candidates see it as one thicker line and have to make more effort to perceive the difference.</td>
</tr>
</table>

<table>
<tr>
<td>
Composite edges with one colour and whole arrowheads

User rating attractiveness:

Very attractive 0
Attractive 4
Neutral 3
Unattractive 3
Very unattractive 2

Three participants find this flow map edge layout the clearest and most applicable.</td>
<td>There is a strong division between the participants in the usability's assessment and application of the composite edges. The proponents think that by combining the forward and backward directions of a flow, the flow map becomes clearer and the connections between nodes are immediately visible. Participants suggest giving each direction in an edge its own colour. This should emphasise the difference in values.

Participants who judge the composite edge negatively have difficulty distinguishing between the values for the outward and the return direction. It is impossible to tell if the difference in values is small. In the situation where there is a short distance between two nodes, the edge distorts depending on the size of the movement flow and the size of the arrow in the edge. This makes it difficult for participants to recognise the edge and the underlying values.</td>
</tr>
<tr>
<td>
Combined edges with different colours and whole arrows

User rating attractiveness:

Very attractive 0
Attractive 3
Neutral 4
Unattractive 3
Very unattractive 2

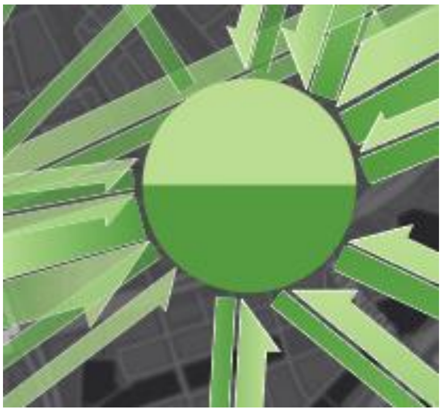
None of the participants finds this flow map edge layout the most clear and applicable.</td>
<td>There is a strong desire among public transport experts to distinguish between modalities in travel flows. The combination of an edge with a colour and a thickness makes it easier to detect the largest flows.

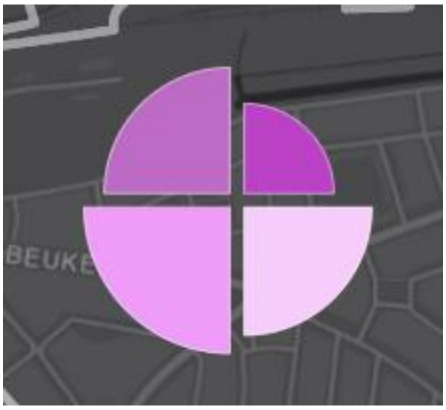
Participants fear that if many origin-destination relations are depicted, the flow map will become unreadable due to overlapping edges and arrows in the edges. Respondents also argue that the flow map contained too much information, making it more difficult to answer a specific question. The participants remarked that the legend should be consulted more often if several hues are used in the flow map.</td>
</tr>
</table>

Table 5: User research results - application of edge variants

The table below summarises the insights from the user research regarding the different node variants.

Node visualisation	Insights
 **Graphical icon symbol** Two of the participants find the graphical icon the most clear and applicable.	One participant finds the graphical icon useful because it clearly shows whether it is the total incoming or outgoing flow into an area. The other respondents comment that they have difficulty in determining, for each node combination, which icon represents the incoming and which the outgoing flow. Respondents look at the legend to understand the meaning of the nodes. Map users find it confusing that an edge can point to an outgoing node when there is no relationship. The direction of the arrows in the same direction is not intuitive. Participants also find it difficult to estimate and compare the size of the icons when the difference between the incoming and outgoing icon is small. If the graphical icon node is smaller than 10 pixels, participants find the icon difficult to read because it is not clear whether the arrow in the icon is pointing inwards or outwards. Two of the 13 participants use the nodes to determine the largest difference between travel flows between neighbourhoods. The other respondents compare the values of the edges or get confused when comparing the values of nodes and edges. A tested variant with graphic icons that correspond to one colour in the edges creates confusion among the respondents. The map readers establish a relationship between the nodes and the edges with a corresponding colour hue.

 **Pie chart node** Ten of the participants find the graphical icon the most clear and applicable.	Participants find the pie chart node clear because in one form the size of the total flow of movements is visible. The node visualises the ratio between the incoming and outgoing flow. Participants note that the node with the light green and dark green hue contrasts strongly with the dark grey base map. The respondents' attention is attracted to the largest node and nodes that are isolated in the map image. The position of the node in a neighbourhood does initially create the feeling among the participants that the flows go to that specific position in an area. In areas with an asymmetrical surface area, this is reinforced because the respondent does not feel that the node is exactly in the middle of the area. Participants need a legend to determine which pie slice represents the incoming or outgoing flow. Only one respondent correctly identified the relationship between the colour gradient in the edge and in the explanation of the two colour shades. The simple layout of the node makes the relationship between the incoming and outgoing movement flows visible even when the total movement flow is small and the node therefore has a small diameter.
 **Wind rose node** Participants see a practical application for the wind rose node.	During the usability test, a variant of the pie chart node was tested. The wind rose node offers an additional dimension to provide information on the flow map. Respondents are of the opinion that a legend is essential to interpret the values in the segments. Most participants could derive the correct value. Respondents also mention other applications for the wind rose node. For example, to identify the number of potential travellers who live within a radius of 400 metres or a 10-minute walk from a stop. Most participants find the wind rose node complex and contain a lot of information. They find it difficult to determine an exact wind direction. Participants remarked that the wind rose node should design differently to make it clear whether a segment points to a specific wind direction. There is also confusion about the edges that visualise relationships between nodes. The edges are not always in line with the wind direction segments. Participants also try to establish a relationship between the edges shown and the number of travellers travelling a

<table>
<tr><td></td><td>certain distance in a wind direction from an area. Respondents advise to leave out the edges because they do not offer any added value.</td></tr>
<tr><td>
Pie chart with quadrants node

Three participants see a practical application for the pie chart with quadrants node.</td><td>The division of the node into four quadrants has various applications. In the usability task, the element time is used. It is difficult for respondents to see a 24-hour clock in the circle. In addition, participants find the hues per segment not logical in relation to the period.

As an alternative application, respondents mention mapping out the market share per modality. Respondents also see possibilities for showing how travellers get to and from a stop (first and last mile).

For map users, it is essential in this node variant that a legend explains the values.</td></tr>
</table>

Table 6: User research results - application of node variants

Based on the tasks performed, the usability of visual variables and flow map features has been investigated. The table below summarises the most important findings.

<table>
<tr><th>Visual variables and flow map features</th><th>Insights</th></tr>
<tr><td>Colour</td><td>A cartographer should take into account visually impaired map readers in the design of flow maps. The user research shows that there can be great differences in the perception of map elements and symbols. Standard design guidelines for colour-blind people are not sufficient in this case.

Participants who are colour blind or who have limited vision remark that they find it difficult to perceive or distinguish symbology with a certain colour scheme. It is essential that the meaning of the colour is explained in the legend, and the number of different shades does not exceed five. The contrast between the colours and the base map should be large enough to perceive symbols. Participants suggest the use of a single hue colour scheme.

For participants, it is logical that light hues represent low values and dark hues represent high values. They need no legend for this.

The colours red and green are automatically associated</td></tr>
</table>

	with good and bad. Most colour-blind people cannot distinguish between the colours green and red. Using diverging hues in the representation of distinct classes requires greater mental effort by map readers. If a blue or purple hue is used besides a red and green hue in the colour scheme, participants show they do not understand what this colour stands for. Participants mention the use of a strongly deviating colour to stress differences in, for example, time. Respondents find elements in the base map with strong contrasting colours distracting and distracting. Using a contrasting stroke around an edge to make it easier to distinguish overlapping edges is noted by one participant as helpful. Another respondent notices the transparency of edges. The participant continues to find it difficult to distinguish between several overlapping edges, despite the transparency. Respondents envision an application for bundled flow map symbology. The saturation of stacked edges increases as more overlap occurs. A second application is made in making layers of data transparent on top of the base map so that the latter remains readable. In the visualisation of social demographic data through polygons, the right choice of colours is important. For example, participants associate green areas in the map with nature areas and do not initially connect with the flow map.
Size	Participants find it difficult to compare the size of nodes further apart in the map when the nodes are the same colour. This is experienced as even more difficult if the incoming and outgoing flow are visualised with two separate nodes. Respondents associate the thickness of the edge with the number of movements between nodes. The differences in thickness between classes should be large enough to distinguish differences. Respondents find the thickness of an edge more difficult to read than a colour. Participants overlook small edges. Participants experience a distortion in the thickness of curved or longer edges. Public transport experts note they bundle flows in their daily work in order to achieve sufficient volume to operate a profitable public transport line. They also expressed this

	in their desire to bring together various transport flows to create a thicker edge. The participants would like a function in the flow map application to aggregate the flows in the flow map. Respondents are looking for edges that bridge a large distance between an origin and destination location. Public transport exporters find this interesting because a longer public transport line offers more chances for a higher return. Some participants perceive longer and curved edges as thinner than shorter edges with the same thickness. Respondents prefer, on average, a minimum line width of 1 pixel to read the value of an edge properly. Participants need a minimum size of 50 pixels for the correct reading of complex node variants such as a wind rose diagram and a minimum size of 30 pixels for a pie chart with four quadrants. For simpler pie charts with only two segments, the values can be observed with a minimum size of 10 pixels. Respondents can only correctly read the direction of movement in a graphic icon if it is at least 10 pixels in size.
Labelling	Respondents answer the question of how important it is to show labels on the flow map: Strongly disagree 0 Disagree 1 Disagree 5 Agree 2 Strongly agree 4 Test candidates consider labels of public transport nodes or destination locations essential in order to name the travel intensity between two areas. Participants prefer to see the exact values of an edge or node in the map. This can also be displayed when clicking on a symbol.

Legend	Respondents look for the legend on a flow map that they see for the first time. The legend removes uncertainty and confirms the first thought or intuition of the map reader. When asked how important the legend is for explaining the elements in the map, the participants answer: Very important 9 Important 2 Not important / Not unimportant 1 Unimportant 0 Very unimportant 0 If certain map elements are missing from the legend, respondents become uncertain and do not know what the symbology represents. If a map element has a specific shape, such as a curved edge or a segment in a pie chart, the participant wants to see that shape in the legend in the same way.
Base map	Most participants prefer the dark grey base map or the topographic base map. The distribution is as follows (multiple answers possible per respondent): Topographic map 5 Dark grey base map 7 Satellite map 0 Light grey base map 3 Contrast plays an important role in the choice of a base map for the participants. In addition, respondents want to perceive clearly recognisable points on the map for orientation. These can be labels, landmarks, buildings or road patterns. Participants expect more detail in the map when it is zoomed in. Depending on the scale level, transport experts want to see the metro, tram and bus network on the base map.
2D versus 3D	Nine respondents strongly preferred a 2D flow map. 2D gives a calmer map image. In a 3D flow map, edges and nodes can disappear behind 3D objects unless the map can be rotated.

Table 7: User research results - insights visual variables and flow map features

4.3 Mental effort

Respondents find it difficult to let go of their own mental map of movements when looking at a flow map. Differences between the two versions are quickly noticed and call for further investigation.

Participants mention small symbols are noticed less quickly and that it takes more effort for them to identify symbols with a lot of detail in the map.

The more small streams that lead to a node, the more a participant adds up values of edges to determine the total stream. The greater the number of colours and thicknesses in the edges and nodes, the greater the effort required of the map reader to remember the values. Participants state that a difference in colouring helps in determining a value, but that a striking colour for another map element is highly distracting. With multiple variables in a flow map where time also plays a role through an animation, participants find it difficult to determine the exact value of a line segment.

4.4 Static flow maps versus dynamic flow maps

Ten of the thirteen participants say they would rather use a dynamic flow map than a static map. The large number of edges and nodes in the first dynamic flow map (see Appendix F) put off a small group of respondents. They put different static maps next to each other when they want to compare multiple variables. Respondents mention that a dynamic flow map should be easy to use without having to spend a lot of time making settings.

4.5 The relationship between participants' spatial knowledge and their performance

The empirical study investigated whether there was a relationship between geographical knowledge, knowledge of the public transport network, and the performance of participants during the usability tasks. We only looked at whether a participant could carry out the assignment correctly. Because some respondents gave their comments about the map first, it is not meaningful to include the time needed to carry out an assignment correctly in the performance measurement. T

From the results in table 8, it can be concluded that policymakers with high geographical and network knowledge perform better in performing the usability tasks based on flow maps than policymakers with low knowledge. This is mainly because the usability test includes questions that require you to know where a certain neighbourhood in the service area is located. Policymakers with a lot of knowledge but with a visual impairment score significantly lower than colleagues with a lot of knowledge and without visual impairments. The influence of colour use and line thickness in the flow maps and symbology plays an essential role here.

Participant	Spatial score		Performance score	Remarks
	Spatial ability geography 1 = low 2 = medium 3 = high	Spatial ability Public transport network 1 = low 2 = medium 3 = high	Performance Usability test - Total number versus correctly performed tasks.	
R1	1	1	15/19	
R2	1	2	9/13	Participant has carried out only 13 assignments
R3	3	3	18/19	
R4	3	3	17/19	
R5	3	3	14/17	Participant has carried out 17 of the 19 assignments
R6	2	2	13/19	
R7	3	3	14/19	
R8	3	3	18/19	
R9	3	3	10/19	Participant has a severe visual impairment
R10	1	2	13/19	
R11	3	3	17/19	
R12	1	1	15/19	
R13	3	3	16/19	Participant is colour blind

Table 8: Spatial ability and knowledge of the network versus performance usability tasks

5 Discussion

The mobility sector is constantly changing. New mobility concepts, the growth of bike sharing systems, large infrastructure projects, the increasing use of electric bicycles and, to an extreme extent, the COVID-19 pandemic, all impact the travel behaviour of the citizens of an area.

Transport experts have to consider more and more factors in their decision-making. Fortunately, more and more data are available to solve mobility issues. Public transport companies are setting up data analysis teams to help decision-makers analyse the vast amount of data. Data analysts understand travel data must be properly visualised for transport experts to use it efficiently and effectively. One of the most common ways of visualising origin-destination data is through a flow map.

This section pulls together the insights from the literature review and the results from the usability test to answer the primary research question of this study:

"*Which cartographic design principles and visual variables of a flow map give transport experts a sound insight into the travel behaviour of citizens, helping to improve public transport services*."

5.1 Mind the gap between map user and cartographer

Today's digital tools make it tempting for a cartographer to pull out all the stops when visualising mobility data. However, the usability test shows that there can be a world of difference between the mindset and working method of the GIS expert and that of the map reader.

Transport experts with little GIS experience prefer simple geo visualisations. Through edges or nodes, flows of movement between origin and destination locations are made visible. Transport experts compare these flow maps with the existing public transport network to determine where improvements can be made. More complex flow maps with symbology like the wind rose diagram or the interactive geo visualisation require a great mental effort from the novice map reader (Appendix C task Flowmap_11 and Flowmap_20).

Policymakers with more experience can apply multi dimensional flow maps faster but still prefer simple visualisations. Interestingly, both experienced and inexperienced map readers see new applications for the complex flow maps. By spending more time on the layering in flow maps, transport experts are made to think and transportation issues are highlighted from new angles. The cartographer must involve the map reader as early as possible in creating a flow map.

5.2 Information requirement, level-of-detail and area definition

The empirical research shows that transport experts mainly look at trips made by the modality of their own interest: car, bus, tram or metro. They are not only looking for insights in numbers of trips, but also in quantities like travel time and speed.

This also has consequences for the desired level-of-detail at which policymakers want to see mobility data presented. Transport experts, when examining the travel behaviour of citizens in the catchment area of a public transport company, start with an overview map of the largest trips. Transport experts want to see landmarks in the base map based on which they can orient themselves. These can be landmarks, the road network or public transport hubs. Map readers want a flow map to be clear without too much clutter. All elements that the user does not need to analyse travel flows or to orient himself must be left out of the flow map.

The area definition and the allocation of trips to an area depend on the mobility problem. Each modality has its own scope and uses a certain type of infrastructure. If only the travel behaviour of bus passengers is analysed, this seems less complex than the analysis of multimodal travel flows. However, journeys made using a specific mode of transport cannot be considered as an isolated event. Movement behaviour via other modalities and the environmental context also influence travel flows. This makes it difficult for a map designer to determine the right level-of-detail of a flow map and the right area division between which movements take place. If a policymaker wants to analyse an area based on the overview map, he will zoom in or select the detailed area based on criteria. The map reader then wants to see additional information in the map to interpret the situation. Transport experts need social demographic data and insight into the distribution of the use of modalities between origin and destinations (modal split).

Public transport experts try to bundle passenger flows that are directed from a neighbourhood to stops in order to travel further by public transport. This is also expressed in their preference for bundling flows between origins and destinations in a flow map. Policymakers recognise the road and rail infrastructure in the curved edges. This corresponds better with their mental map of the public transport network than with the sky-wide edges between origins and destinations. However, a distorted picture may arise if parallel public transport lines are merged into a single flow that does not follow the exact route of the largest flow, for example.

The scale level of the flow map strongly determines the extent to which the map offers space for supporting information without masking the movement data. The cartographer will have to find the right balance between the readability and the information value of the flow map.

5.3 Properties that a flow map should meet for decision-making in public transport

As noted in the literature review, scholars are divided on whether a straight or curved edge is the most useful in analysing travel behaviour. The interviewed transport experts are not unanimous on this. However, there is a strong preference for visualising passenger volumes through colours rather than line widths. Transport experts find that overlapping edges in a flow map are unreadable. Overlap can be reduced by omitting small and short flows from the flow map. The policymaker can do this by filtering on minimum passenger numbers per route in a period and by setting a minimum travel distance.

The overview map mentioned earlier suffices for map readers by showing straight edges. Volumes of travel can best be divided into a maximum of four or five classes. For each class, the edges should have a clearly distinguishable colour that contrasts sufficiently with a dark grey base map. It is logical for transport experts that a light colour tone represents a lower volume than a dark tone. Using a GIS or a web mapping application offers the possibility to let the map reader compose a readable colour scheme or base map himself. This enables even visually impaired policymakers to perceive the most important traffic flows.

A GIS expert can also choose to give edges a line thickness based on the classes. This is only useful if it prevents the edges from overlapping. To show the direction of a flow, transport experts prefer edges with a full arrow. If the edges' arrowheads are in danger of overlapping, half an arrowhead may be used.

To show the proportion of trips between origin and destination for an area, a pie chart works best for transportation experts. Instead of depicting a node in an area, the edges can also form an open circle

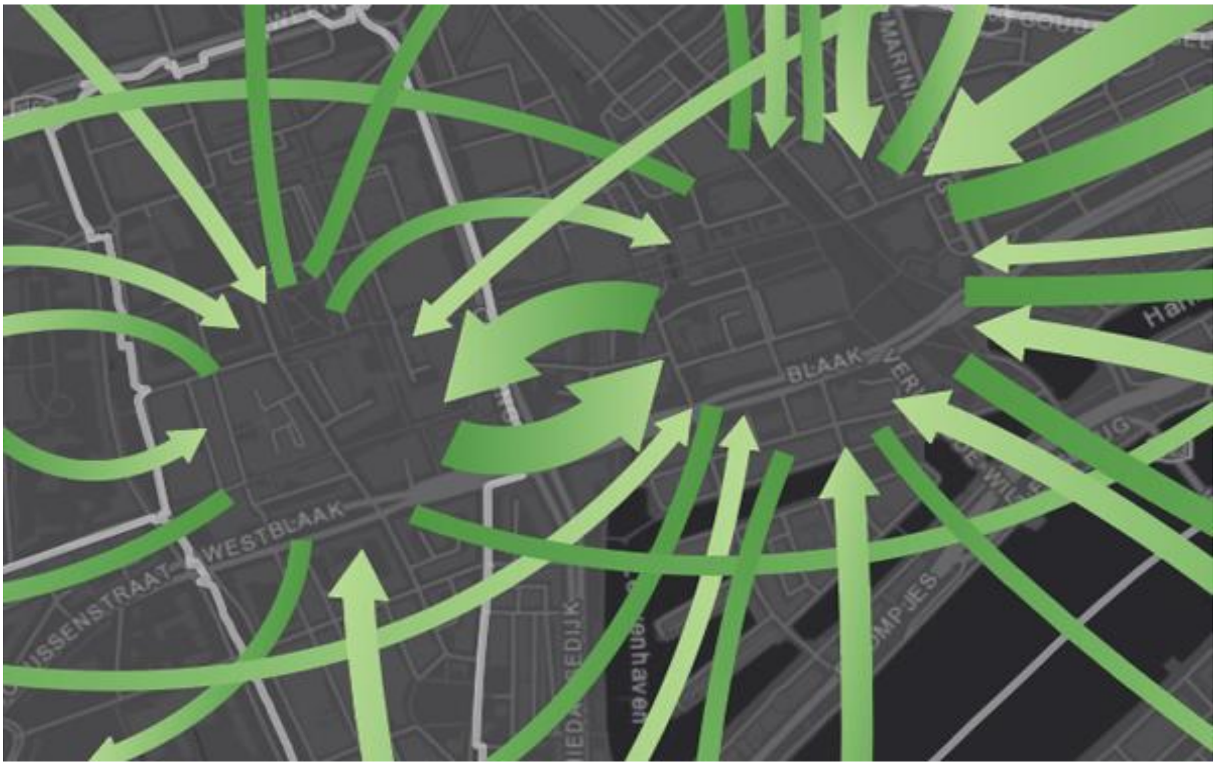


Figure 6: Creation of an open node

(see figure 6). The size of the node visualises the total flow. In a pie chart, two segments represent the incoming and outgoing movements and add up to 100%. Policymakers find pie chart nodes easier to interpret than graphical icon symbols because there is no confusion with edges about the direction of travel and colouring. By keeping minimum volumes that are visualised in the flow map, the problem of poor legibility of small nodes is also overcome. The minimum widths for edges and size of nodes (Field, 2018) described in the literature turned out to be too small in the usability test to be correctly perceived by the map readers.

The distribution of the use of different modalities between origin and destination is difficult to visualise in an edge. A flow map quickly becomes confusing because of the mass of coloured lines per modality. In addition, each modality has its own route, travel distance and speed. This can be partially solved by creating a flow map for each modality and comparing them. Another solution is to superimpose the modalities as map layers in a dynamic map.

If the flow map symbology meets the desired specifications, the transport expert positions the public transport network under the flow map. Based on the observed differences, a policymaker can determine where opportunities lie to improve the public transport network.

5.4 Static and dynamic flow maps

Transport experts prefer a dynamic flow to a static variant. They use a dynamic flow map to examine a specific area. Map users want to select origins and destinations and subdivide modalities based on certain criteria. This offers a solution for the previously outlined limitations of static flow maps. Respondents expect to visualise interesting traffic flows in the enormous mass of edges and nodes through the map functions offered. Especially the possibility of adjusting the map composition in the dynamic flow map to the information needs and visualisation preferences appeals to policymakers. They want to make detailed information visible by dynamic labelling or a pop-up.

In the dynamic flow map, transport experts want to switch layers on and off with social demographic and infrastructural information in order to make cross connections. Depending on their information needs, transport experts want to see more or less information on the map by zooming in or out or by switching map layers on or off. The resolution of the areas (districts, neighbourhoods, four- and five-digit postal code areas) and the main destination locations between which journeys take place should be scaled accordingly.

The amount of data and the different map functions presented in a dynamic map overwhelm the transport experts who prefer a static flow. These policymakers are of the opinion that a table with origins and destinations gives a quicker insight into movements. This will certainly be the case with a few movements in a small area. For a service area of 500 km² with hundreds of thousands of daily movements by bicycle, public transport and car, a dynamic flow map supplemented with social demographic data provides insights in a geographical context that cannot be deduced from a table. An alternative solution for policymakers who want to combine large amounts of data with flow maps is visual analytics. Visual analytics is the science of analytical reasoning supported by interactive visual interfaces (Keim et al., 2009).

Static flow maps can easily be included in reports and presentations as a derivative of a dynamic flow map to support a decision. Involving the map reader earlier in the design process of the dynamic flow map and the map functions offered will increase the involvement of the user and the usability of the flow map.

5.5 The influence of the policymaker's spatial ability and knowledge of the public transport network on the presentation of flow map symbology

Transport experts with an excellent knowledge of the geography of the service area and the public transport network performed the usability tasks better than policymakers with a low knowledge of the geography and the network.

Transport experts with good geographical and network knowledge but with a visual impairment scored worse when performing the tasks. For this group, it is especially important that the flow map symbology matches the user's visual capacity. This mainly concerns minimal line thickness and colour contrast. The usability test and post-questionnaire revealed that transport experts with little knowledge of the geography of the service area and public transport network are best served by curved edges with a colour per class and graphic icons that visualise the relationship between incoming and outgoing flows.

Policymakers with an average level of knowledge of the geography and the network prefer straight edges where the line thickness displays the passenger volumes and a pie chart shows the ratio of inbound and outbound trips for an area.

Map readers with the most experience and knowledge of the service area and network strongly prefer straight and coloured edges and pie chart nodes. When the number of movements in an area of interest is large, this group of users prefers the composite edge to reduce overlap in the flow map. For a clearer distinction between the two directions, a distinctive colour per direction is suggested.

6 Conclusion

Based on the insights gathered from the literature review and the qualitative research, the researcher urges scholars to take a more in-depth look at the role of non-experts in the development of user-centred geo visualisations that allow transport experts to discover and analyse movement data.

A thorough understanding of how non-experts work by Geo scientists aims to provide GIS experts with design guidelines and a toolbox for the generation of usable flow maps.

For the GIS experts the most important and obvious conclusion that can be drawn from this research is that the early involvement of transport experts in the design process of the flow map symbology and map functions is essential.

Even among a specific professional group such as transport experts, there is a big difference in knowledge and experience of geographical data and map applications. The information needs of the decision-makers vary widely and require different levels of detail. These differences also require that movement behaviour is visualised specifically for each transport expert. This way visual limitations of the map reader or GIS skills can also be considered.

Transport experts recognise the advantages of dynamic flow maps over static variants. GIS and web mapping applications allow GIS experts to show only movement data that is relevant for the transport expert. Contemporary online map applications offer map readers functions and personalisation possibilities to adjust the colour and line thickness of nodes and edges to their personal preferences.

Not every policymaker needs this option and may even find it complicated. An onboarding process in which the map reader sets the symbology options can overcome this.
Of course, involving the transport expert in the design process requires extra effort from both the cartographer and the map reader. The quality of the decisions based on a user-centred flow map will ultimately produce a better result for a public transport company.

7 Limitations and future research

Because of COVID-19 and the related lockdown, the usability research had to take place online. Therefore, it was not possible to use eye-tracking to measure exactly how much effort a participant had to put in to execute a task. Also, it was not possible to measure how transport experts viewed the different flow map symbology variants in relation to their comments. Conducting a user survey online also has the limitation that different computers were used by the respondents with different screen settings, CPU speed and internet speed. This can influence how the candidate perceives the flow map on the screen.

Because extensive qualitative research per subject was chosen, only a few transport experts could be interviewed because of limited time.

The research into the application of flow map symbology for better decision-making in public transport has not only provided a lot of insights and answers, but has also led to new questions. First, it is recommended to repeat the usability test, but then including the measurement of eye movements and mental effort through eye-tracking. Second, it is advisable to test specific findings and substantiate them statistically by a quantitative study. Not only among transport experts but also among policymakers responsible for the accessibility of urban areas.

In this study, dynamic flow maps were only a small part of the research. The results show that transport experts have a strong preference for this flow map variant. Research on alternative variants of flow maps and symbology based on web technologies such as D3.js, flowmap.gl or flow map plug-ins for ArcGIS or QGIS is therefore advisable.

Finally, the most important insight gained from this research is the early involvement of the map reader in the design of the flow map and the functions offered in a flow map. It is recommended that a study be started in which this user-centred design process is followed and its impact compared to the traditional creation of flow maps.

References

Albers, M.J. and Quesenberry, W., 2003. *Content & Complexity.* [online] Milton: Taylor & Francis. Available at: <https://public.ebookcentral.proquest.com/choice/publicfullrecord.aspx?p=5300780> [Accessed 24 Aug. 2020].

Anon 1998. *ISO 9241-11: Ergonomic requirements for office work with visual display terminals (VDTs): Part 11: Guidance on usability.*

Anon 2017. *Eindrapport Analyse- en Oplossingsrichtingenfase MIRT-onderzoek Bereikbaarheid Rotterdam Den Haag*. Gemeente Rotterdam. Gemeente Den Haag, Provincie Zuid-Holland, Metropoolregio Rotterdam Den Haag, Ministerie van Infrastructuur en Milieu.

Anon 2019. *Onderweg in Nederland (ODIN)*. CBS.

Baddeley, A., 1995. *Working memory*. Reprint ed. Oxford psychology series. Oxford: Clarendon Press.

Baddeley, A.D., 1999. *Essentials of human memory*. Cognitive psychology. Hove, England: Psychology Press.

Bakker, P., 2020. *Kerncijfers Mobiliteit 2020*. [online] Den Haag: Kennisinstituut voor Mobiliteitsbeleid. Available at: <https://www.kimnet.nl/publicaties/rapporten/2020/10/28/kerncijfers-mobiliteit-2020>.

Bertin, J., 1983. *Semiology of graphics*. Madison, Wis: University of Wisconsin Press.

Bier, E.A., Stone, M.C., Pier, K., Buxton, W. and DeRose, T.D., 1993. Toolglass and magic lenses: the see-through interface. In: *Proceedings of the 20th annual conference on Computer graphics and interactive techniques - SIGGRAPH '93*. [online] the 20th annual conference. Not Known: ACM Press.pp.73–80. https://doi.org/10.1145/166117.166126.

Boyandin, I., 2020. *Flowmap Blue*. Available at: <https://flowmap.blue/> [Accessed 20 Oct. 2020].

Boyandin, I., Bertini, E. and Lalanne, D., 2010. Using flow maps to explore migrations over time. In: 3. Geospatial Visual Analytics Workshop in conjunction with The 13th AGILE International Conference on Geographic Information Science. .

Brewer, C.A., 1997. Spectral Schemes: Controversial Color Use on Maps. *Cartography and Geographic Information Systems*, 24(4), pp.203–220. https://doi.org/10.1559/152304097782439231.

Brewer, C.A., 2005. *Designing better maps: a guide for GIS users*. 1st ed ed. Redlands, Calif: ESRI Press.

Buchin, K., Speckmann, B. and Verbeek, K., 2011. Flow Map Layout via Spiral Trees. *IEEE Transactions on Visualization and Computer Graphics*, 17(12), pp.2536–2544. https://doi.org/10.1109/TVCG.2011.202.

Buckner, R.L. and Tulving, E., 1995. Neuroimaging studies of memory: theory and recent PET results. *Handbook of neuropsychology*, 10, pp.439–439.

Carpendale, S., 2008. Evaluating Information Visualizations. In: A. Kerren, J.T. Stasko, J.-D. Fekete and C. North, eds. *Information Visualization*, Lecture Notes in Computer Science. [online] Berlin, Heidelberg: Springer Berlin Heidelberg.pp.19–45. https://doi.org/10.1007/978-3-540-70956-5_2.

Carroll, J.S. and Johnson, E.J., 1990. *Decision research: a field guide*. [online] Newbury Park: Sage Publications. Available at: <http://books.google.com/books?id=M019AAAAMAAJ> [Accessed 6 Aug. 2019].

Castner, H.W. and Eastman, R.J., 1985. Eye-Movement Parameters and Perceived Map Complexity—II. *The American Cartographer*, 12(1), pp.29–40. https://doi.org/10.1559/152304085783914712.

Cauvin, C., Escobar, F. and Serradj, A., 2013. *Thematic Cartography and Transformations: Cauvin/Thematic Cartography and Transformations*. [online] Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9781118558133.

Clifford, N.J., Cope, M., Gillespie, T.W. and French, S. eds., 2016. *Key methods in geography*. Third edition ed. London: SAGE.

Denègre, J. ed., 2005. *Sémiologie et conception cartographique*. Collection ENSG-IGN. Paris: Hermès science publications.

Dent, B.D., Torguson, J. and Hodler, T.W., 2009. *Cartography: thematic map design*. 6th ed ed. New York: McGraw-Hill Higher Education.

DGBRW Directie Woningmarkt, 2020. *Staat van de Woningmarkt 2020*. Available at: <https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/kamerstukken/2020/06/15/kamerbrief-staat-van-de-woningmarkt-2020/aanbieding-staat-van-de-woningmarkt-2020.pdf> [Accessed 2 Dec. 2020].

DiBiase, D., MacEachren, A.M., Krygier, J.B. and Reeves, C., 1992. Animation and the Role of Map Design in Scientific Visualization. *Cartography and Geographic Information Systems*, 19(4), pp.201–214. https://doi.org/10.1559/152304092783721295.

Dobson, M.W., 1985. The future of perceptual cartography. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 22(2), pp.27–43. https://doi.org/10.3138/E482-2512-732Q-2T11.

Dong, W., Wang, S., Chen, Y. and Meng, L., 2018. Using Eye Tracking to Evaluate the Usability of Flow Maps. *ISPRS International Journal of Geo-Information*, 7(7), p.281. https://doi.org/10.3390/ijgi7070281.

Downs, R.M. and Stea, D., 1977. *Maps in minds: reflections on cognitive mapping*. Harper & Row series in geography. New York: Harper & Row.

Erskine, M., Gregg, D., Karimi, J. and Scott, J., 2013. Business Decision-Making Using Geospatial Data: A Research Framework and Literature Review. *Axioms*, 3(1), pp.10–30. https://doi.org/10.3390/axioms3010010.

Esri, 2020. *Dark Gray Canvas Base (WGS84)*. Available at: <https://www.arcgis.com/sharing/rest/content/items/55253142ea534123882314f0d880ddab/resources/styles/root.json> [Accessed 20 Oct. 2020].

Fabrikant, S.I., Hespanha, S.R. and Hegarty, M., 2010. Cognitively Inspired and Perceptually Salient Graphic Displays for Efficient Spatial Inference Making. *Annals of the Association of American Geographers*, 100(1), pp.13–29. https://doi.org/10.1080/00045600903362378.

Field, K., 2018. *Cartography: a compendium of design thinking for mapmakers*. Redlands, California: Esri Press.

Forsell, C. and Cooper, M., 2014. An Introduction and Guide to Evaluation of Visualization Techniques Through User Studies. In: W. Huang, ed. *Handbook of Human Centric Visualization*. [online] New York, NY: Springer New York.pp.285–313. https://doi.org/10.1007/978-1-4614-7485-2_11.

Froehlich, J., Neumann, J. and Oliver, N., 2008. Measuring the Pulse of the City through Shared Bicycle Programs. International Workshop on Urban, Community, and Social Applications of Networked Sensing Systems. Raleigh, North Carolina.

Garlandini, S. and Fabrikant, S.I., 2009. Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization. In: K.S. Hornsby, C. Claramunt, M. Denis and G. Ligozat, eds. *Spatial Information Theory*, Lecture Notes in Computer Science. [online] Berlin, Heidelberg: Springer Berlin Heidelberg.pp.195–211. https://doi.org/10.1007/978-3-642-03832-7_12.

Gar-on, Y., Shuangming, Z., Jianya, G. and Xinyan, Z., 2001. Design and implementation of dynamic symbols in dynamic GIS. *Geo-spatial Information Science*, 4(4), pp.32–36. https://doi.org/10.1007/BF02826575.

Gemeente Rotterdam, 2019. *Strategische verkenning verstedelijking*. [online] Rotterdam. Available at: <https://rotterdam.raadsinformatie.nl/document/7827160/1/s19bb017999_3_50801_tds> [Accessed 2 Dec. 2020].

Giannotti, F. and Pedreschi, D. eds., 2008. *Mobility, Data Mining and Privacy*. [online] Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-75177-9.

Gopher, D. and Braune, R., 1984. On the Psychophysics of Workload: Why Bother with Subjective Measures? *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 26(5), pp.519–532. https://doi.org/10.1177/001872088402600504.

Gould, J.D. and Lewis, C., 1983. Designing for usability---key principles and what designers think. In: *Proceedings of the SIGCHI conference on Human Factors in Computing Systems - CHI '83*. [online] the SIGCHI conference. Boston, Massachusetts, United States: ACM Press.pp.50–53. https://doi.org/10.1145/800045.801579.

de Graaf, S.W., Veurink, E.J. and Lodder, H., 2017. Nieuw data-driven verkeersmodel MRDH modelleert nu met fiets- OV-keten ook de sterkst groeiende modaliteiten beter. Colloquium Vervoersplanologisch Speurwerk. .

Guan, Z., Lee, S., Cuddihy, E. and Ramey, J., 2006. The validity of the stimulated retrospective think-aloud method as measured by eye tracking. In: *Proceedings of the SIGCHI conference on Human Factors in computing systems - CHI '06*. [online] the SIGCHI conference. Montréal, Québec, Canada: ACM Press.p.1253. https://doi.org/10.1145/1124772.1124961.

Guo, D., 2009. Flow Mapping and Multivariate Visualization of Large Spatial Interaction Data. *IEEE Transactions on Visualization and Computer Graphics*, 15(6), pp.1041–1048. https://doi.org/10.1109/TVCG.2009.143.

Guo, D. and Zhu, X., 2014. Origin-Destination Flow Data Smoothing and Mapping. *IEEE Transactions on Visualization and Computer Graphics*, 20(12), pp.2043–2052. https://doi.org/10.1109/TVCG.2014.2346271.

Han, S.Y., Clarke, K.C. and Tsou, M.-H., 2017. Animated Flow Maps for Visualizing Human Movement: Two Demonstrations with Air Traffic and Twitter Data. In: *Proceedings of the 1st ACM SIGSPATIAL Workshop on Analytics for Local Events and News - LENS'17*. [online] the 1st ACM SIGSPATIAL Workshop. Redondo Beach, CA, USA: ACM Press.pp.1–10. https://doi.org/10.1145/3148044.3148049.

Haniff, D.J. and Baber, C., 2003. User evaluation of augmented reality systems. In: *Proceedings on Seventh International Conference on Information Visualization, 2003. IV 2003.* [online] Seventh International Conference on Information Visualization - IV 2003 - International Conference on Computer Visualization and Graphics Applications. London, UK: IEEE Comput. Soc.pp.505–511. https://doi.org/10.1109/IV.2003.1218032.

Harrower, M., 2007. The Cognitive Limits of Animated Maps. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 42(4), pp.349–357. https://doi.org/10.3138/carto.42.4.349.

He, J., Chen, H., Chen, Y., Tang, X. and Zou, Y., 2019. Diverse Visualization Techniques and Methods of Moving-Object-Trajectory Data: A Review. *ISPRS International Journal of Geo-Information*, 8(2), p.63. https://doi.org/10.3390/ijgi8020063.

Holten, D. and van Wijk, J.J., 2009. A user study on visualizing directed edges in graphs. In: *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09*. [online] the SIGCHI Conference. Boston, MA, USA: ACM Press.p.2299. https://doi.org/10.1145/1518701.1519054.

Jarupathirun, S. and Zahedi, F. "Mariam", 2007. Exploring the influence of perceptual factors in the success of web-based spatial DSS. *Decision Support Systems*, 43(3), pp.933–951. https://doi.org/10.1016/j.dss.2005.05.024.

Jenks, G.F. and Knos, D.S., 1961. THE USE OF SHADING PATTERNS IN GRADED SERIES [1]. *Annals of the Association of American Geographers*, 51(3), pp.316–334. https://doi.org/10.1111/j.1467-8306.1961.tb00381.x.

Jenny, B., Stephen, D.M., Muehlenhaus, I., Marston, B.E., Sharma, R., Zhang, E. and Jenny, H., 2018. Design principles for origin-destination flow maps. *Cartography and Geographic Information Science*, 45(1), pp.62–75. https://doi.org/10.1080/15230406.2016.1262280.

Keates, J.S., 1996. *Understanding maps*. 2. ed ed. Harlow: Longman.

Keim, D.A., Mansmann, F., Stoffel, A. and Ziegler, H., 2009. Visual Analytics. In: L. Liu and M.T. Özsu, eds. *Encyclopedia of Database Systems*. [online] Boston, MA: Springer US.pp.3341–3346. https://doi.org/10.1007/978-0-387-39940-9_1122.

Kim, S., Jeong, S., Woo, I., Jang, Y., Maciejewski, R. and Ebert, D.S., 2018. Data Flow Analysis and Visualization for Spatiotemporal Statistical Data without Trajectory Information. *IEEE Transactions on Visualization and Computer Graphics*, 24(3), pp.1287–1300. https://doi.org/10.1109/TVCG.2017.2666146.

Koláčný, A., 1969. Cartographic Information—a Fundamental Concept and Term in Modern Cartography. *The Cartographic Journal*, 6(1), pp.47–49. https://doi.org/10.1179/caj.1969.6.1.47.

Korpi, J. and Ahonen-Rainio, P., 2013. Clutter Reduction Methods for Point Symbols in Map Mashups. *The Cartographic Journal*, 50(3), pp.257–265. https://doi.org/10.1179/1743277413Y.0000000065.

Koua, E.L., Maceachren, A. and Kraak, M. -J., 2006. Evaluating the usability of visualization methods in an exploratory geovisualization environment. *International Journal of Geographical Information Science*, 20(4), pp.425–448. https://doi.org/10.1080/13658810600607550.

Koylu, C., 2014. *Understanding Geo-Social Network Patterns: Computation, Visualization, and Usability*. [online] University of South Carolina. Available at: <https://scholarcommons.sc.edu/etd/3031/> [Accessed 2 Jan. 2020].

Koylu, C. and Guo, D., 2017. Design and evaluation of line symbolizations for origin–destination flow maps. *Information Visualization*, 16(4), pp.309–331. https://doi.org/10.1177/1473871616681375.

Kraak, M.J. and Ormeling, F., 2010. *Cartography: visualization of geospatial data*. 3rd ed ed. Harlow ; New York: Prentice Hall.

Krell, M., 2017. Evaluating an instrument to measure mental load and mental effort considering different sources of validity evidence. *Cogent Education*, [online] 4(1). https://doi.org/10.1080/2331186X.2017.1280256.

Kulhavy, R.W. and Stock, W.A., 1996. How cognitive maps are learned and remembered. *Annals of the Association of American Geographers*, 86, pp.123–145.

Kulyk, O., Kosara, R., Urquiza, J. and Wassink, I., 2007. Human-Centered Aspects. In: A. Kerren, A. Ebert and J. Meyer, eds. *Human-Centered Visualization Environments*, Lecture Notes in Computer Science. [online] Berlin, Heidelberg: Springer Berlin Heidelberg.pp.13–75. https://doi.org/10.1007/978-3-540-71949-6_2.

Kwan, M., 2012. *Visualization and analysis of mobile phone location data*. Royal Melbourn Iinstitute of Technology.

Lloyd, R., 1997. Visual Search Processes Used in Map Reading. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 34(1), pp.11–32. https://doi.org/10.3138/F342-1217-827R-0777.

MacEachren, A.M., 1982. The Role of Complexity and Symbolization Method in Thematic Map Effectiveness. *Annals of the Association of American Geographers*, 72(4), pp.495–513. https://doi.org/10.1111/j.1467-8306.1982.tb01841.x.

MacEachren, A.M., 1995. *How maps work: representation, visualization and design*. New York, N.Y.: Guilford.

Matlin, M.W., 2005. *Cognition*. 6th ed ed. New York: J. Wiley & Sons.

Mennecke, B.E., Crossland, M.D. and Killingsworth, B.L., 2000. Is a Map More than a Picture? The Role of SDSS Technology, Subject Characteristics, and Problem Complexity on Map Reading and Problem Solving. *MIS Quarterly*, 24(4), p.601. https://doi.org/10.2307/3250949.

Modjeska, D., 1997. *Navigation in Electronic Worlds:Research Review for Depth Oral Exam*. University of Toronto.

Montello, D.R. and Sutton, P.C., 2013. *An introduction to scientific research methods in geography & environmental studies*. 2nd ed ed. London ; Thousand Oaks, Calif: SAGE.

Mowafy, L., Blake, R. and Lappin, J.S., 1990. Detection and discrimination of coherent motion. *Perception & Psychophysics*, 48(6), pp.583–592. https://doi.org/10.3758/BF03211604.

Netzel, R., Burch, M. and Weiskopf, D., 2014. Comparative Eye Tracking Study on Node-Link Visualizations of Trajectories. *IEEE Transactions on Visualization and Computer Graphics*, 20(12), pp.2221–2230. https://doi.org/10.1109/TVCG.2014.2346420.

Nielsen, J., 1994. Estimating the number of subjects needed for a thinking aloud test. *International Journal of Human-Computer Studies*, 41(3), pp.385–397. https://doi.org/10.1006/ijhc.1994.1065.

Nielsen, J., 2010. *Usability engineering*. Nachdr. ed. Amsterdam: Kaufmann.

Nocke, T., Buschmann, S., Donges, J.F., Marwan, N., Schulz, H.-J. and Tominski, C., 2015. Review: visual analytics of climate networks. *Nonlinear Processes in Geophysics*, 22(5), pp.545–570. https://doi.org/10.5194/npg-22-545-2015.

Olson, J.M., 1979. COGNITIVE CARTOGRAPHIC EXPERIMENTATION. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 16(1), pp.34–44. https://doi.org/10.3138/R342-258H-5K6N-4351.

Olson, J.M., 2015. Perception and Map Design. *History of Cartography*, 6: Cartography in the Twentieth Century, pp.1063–1065.

Ooms, K., 2012. *Maps, how do users see them. An in depth investigation of the map users' cognitive processes*. Ghent University.

Ooms, K., De Maeyer, P. and Fack, V., 2014. Study of the attentive behavior of novice and expert map users using eye tracking. *Cartography and Geographic Information Science*, 41(1), pp.37–54. https://doi.org/10.1080/15230406.2013.860255.

Opach, T., Korycka-Skorupa, J., Karsznia, I., Nowacki, T., Gołębiowska, I. and Rød, J.K., 2019. Visual clutter reduction in zoomable proportional point symbol maps. *Cartography and Geographic Information Science*, 46(4), pp.347–367. https://doi.org/10.1080/15230406.2018.1490202.

Openshaw, S., 1984. The modifiable areal unit problem. *Concepts and techniques in modern geography*.

Ottosson, T., 1988. What does it take to read a map? *Cartographica: The International Journal for Geographic Information and Geovisualization*, 25(4), pp.28–35. https://doi.org/10.3138/RH17-M777-H206-1570.

Ozimec, A.-M., Natter, M. and Reutterer, T., 2010. Geographical Information Systems–Based Marketing Decisions: Effects of Alternative Visualizations on Decision Quality. *Journal of Marketing*, 74(6), pp.94–110. https://doi.org/10.1509/jmkg.74.6.94.

Paas, F., Renkl, A. and Sweller, J., 2003. Cognitive Load Theory and Instructional Design: Recent Developments. *Educational Psychologist*, 38(1), pp.1–4. https://doi.org/10.1207/S15326985EP3801_1.

Parks, M.J., 1987. *American flow mapping: A survey of the flow maps found in the twentieth century geography textbooks, including a classification of the various flow map designs.* Georgia StateUniversity.

Payne, J.W., Bettman, J.R. and Johnson, E.J., 1993. *The adaptive decision maker*. Cambridge ; New York, NY, USA: Cambridge University Press.

Phan, D., Xiao, L., Yeh, R., Hanrahan, P. and Winograd, T., 2005. Flow map layout. In: *IEEE Symposium on Information Visualization, 2005. INFOVIS 2005.* [online] IEEE Symposium on Information Visualization, 2005. INFOVIS 2005. Minneapolis, MN, USA: IEEE.pp.219–224. https://doi.org/10.1109/INFVIS.2005.1532150.

Purchase, H.C., 2014. Twelve years of diagrams research. *Journal of Visual Languages & Computing*, 25(2), pp.57–75. https://doi.org/10.1016/j.jvlc.2013.11.004.

Purchase, H.C., Cohen, R.F. and James, M., 1996. Validating graph drawing aesthetics. In: F.J. Brandenburg, ed. *Graph Drawing*, Lecture Notes in Computer Science. [online] Berlin, Heidelberg: Springer Berlin Heidelberg.pp.435–446. https://doi.org/10.1007/BFb0021827.

Robinson, A.C., Demšar, U., Moore, A.B., Buckley, A., Jiang, B., Field, K., Kraak, M.-J., Camboim, S.P. and Sluter, C.R., 2017. Geospatial big data and cartography: research challenges and opportunities for making maps that matter. *International Journal of Cartography*, 3(sup1), pp.32–60. https://doi.org/10.1080/23729333.2016.1278151.

Roth, R.E., Çöltekin, A., Delazari, L., Filho, H.F., Griffin, A., Hall, A., Korpi, J., Lokka, I., Mendonça, A., Ooms, K. and van Elzakker, C.P.J.M., 2017. User studies in cartography: opportunities for empirical research on interactive maps and visualizations. *International Journal of Cartography*, 3(sup1), pp.61–89. https://doi.org/10.1080/23729333.2017.1288534.

Rubin, J. and Chisnell, D., 2008. *Handbook of usability testing: how to plan, design, and conduct effective tests*. 2nd ed ed. Indianapolis, IN: Wiley Pub.

Shneiderman, B., 1996. The eyes have it: a task by data type taxonomy for information visualizations. In: *Proceedings 1996 IEEE Symposium on Visual Languages*. [online] 1996 IEEE Symposium on Visual Languages. Boulder, CO, USA: IEEE Comput. Soc. Press.pp.336–343. https://doi.org/10.1109/VL.1996.545307.

Slocum, T.A., Blok, C., Jiang, B., Koussoulakou, A., Montello, D.R., Fuhrmann, S. and Hedley, N.R., 2001. Cognitive and Usability Issues in Geovisualization. *Cartography and Geographic Information Science*, 28(1), pp.61–75. https://doi.org/10.1559/152304001782173998.

Slocum, T.A., McMaster, R.B., Kessler, F.C. and Howard, H.H., 2009. *Thematic cartography and geovisualization*. 3rd ed ed. Prentice Hall series in geographic information science. Upper Saddle River, NJ: Pearson Prentice Hall.

Song, Y., Fan, Y., Li, X. and Ji, Y., 2018. Multidimensional visualization of transit smartcard data using space–time plots and data cubes. *Transportation*, 45(2), pp.311–333. https://doi.org/10.1007/s11116-017-9790-2.

Speier and Morris, 2003. The Influence of Query Interface Design on Decision-Making Performance. *MIS Quarterly*, 27(3), p.397. https://doi.org/10.2307/30036539.

Stanford University and Steiner, E., 2019. Flow Maps. *Geographic Information Science & Technology Body of Knowledge*, [online] 2019(Q4). https://doi.org/10.22224/gistbok/2019.4.10.

Stephen, D.M. and Jenny, B., 2017. Automated layout of origin–destination flow maps: U.S. county-to-county migration 2009–2013. *Journal of Maps*, 13(1), pp.46–55. https://doi.org/10.1080/17445647.2017.1313788.

Stewart, C., Diab, E., Bertini, R. and El-Geneidy, A., 2016. Perspectives on Transit: Potential Benefits of Visualizing Transit Data. *Transportation Research Record: Journal of the Transportation Research Board*, 2544(1), pp.90–101. https://doi.org/10.3141/2544-11.

Tao, S., Rohde, D. and Corcoran, J., 2014. Examining the spatial–temporal dynamics of bus passenger travel behaviour using smart card data and the flow-comap. *Journal of Transport Geography*, 41, pp.21–36. https://doi.org/10.1016/j.jtrangeo.2014.08.006.

Tobler, W.R., 1987. Experiments In Migration Mapping By Computer. *The American Cartographer*, 14(2), pp.155–163. https://doi.org/10.1559/152304087783875273.

Tominski, C., Gladisch, S., Kister, U., Dachselt, R. and Schumann, H., 2017. Interactive Lenses for Visualization: An Extended Survey: Interactive Lenses for Visualization. *Computer Graphics Forum*, 36(6), pp.173–200. https://doi.org/10.1111/cgf.12871.

Tu Huynh, N. and Doherty, S.T., 2007. Digital Sketch-Map Drawing as an Instrument to Collect Data about Spatial Cognition. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 42(4), pp.285–296. https://doi.org/10.3138/carto.42.4.285.

Tufte, E.R., 2001. *The visual display of quantitative information*. 2. ed ed. Cheshire, Conn: Graphics Press.

Tyner, J.A., 2010. *Principles of map design*. New York: Guilford Press.

Vessey, I., 1991. Cognitive Fit: A Theory-Based Analysis of the Graphs Versus Tables Literature. *Decision Sciences*, 22(2), pp.219–240. https://doi.org/10.1111/j.1540-5915.1991.tb00344.x.

Wehrend, S., 1993. Taxonomy of Visualization Goals. *IEEE Computer Society Press:*, pp.187–199.

Wertheimer, M., 1923. Untersuchungen zur Lehre von der Gestalt. II. *Psychologische Forschung*, 4(1), pp.301–350. https://doi.org/10.1007/BF00410640.

Wood, C.H., 1993. VISUAL SEARCH CENTRALITY AND MINIMUM MAP SIZE. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 30(4), pp.32–44. https://doi.org/10.3138/6MRL-3547-07TH-L528.

Wood, D. and Fels, J., 1986. Designs On Signs / Myth And Meaning In Maps. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 23(3), pp.54–103. https://doi.org/10.3138/R831-50R3-7247-2124.

Wood, J., Dykes, J. and Slingsby, A., 2010. Visualisation of Origins, Destinations and Flows with OD Maps. *The Cartographic Journal*, 47(2), pp.117–129. https://doi.org/10.1179/000870410X12658023467367.

Wood, J., Slingsby, A. and Dykes, J., 2011. Visualizing the Dynamics of London's Bicycle-Hire Scheme. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 46(4), pp.239–251. https://doi.org/10.3138/carto.46.4.239.

Xu, K., Rooney, C., Passmore, P., Ham, D.-H. and Nguyen, P.H., 2012. A User Study on Curved Edges in Graph Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 18(12), pp.2449–2456. https://doi.org/10.1109/TVCG.2012.189.

Yang, C., Wu, H., Huang, Q., Li, Z. and Li, J., 2011. Using spatial principles to optimize distributed computing for enabling the physical science discoveries. *Proceedings of the National Academy of Sciences*, 108(14), pp.5498–5503. https://doi.org/10.1073/pnas.0909315108.

Zhao, Y., Tang, X., Sun, F., Zhang, Y. and Wu, Y., 2018. Optimization Strategies of Flow Line Design in Geo-Infographics. In: *2018 26th International Conference on Geoinformatics*. [online] 2018 26th International Conference on Geoinformatics. Kunming: IEEE.pp.1–6. https://doi.org/10.1109/GEOINFORMATICS.2018.8557186.

Zheng, R. ed., 2009. *Cognitive Effects of Multimedia Learning:* [online] IGI Global. https://doi.org/10.4018/978-1-60566-158-2.

Zhou, H., Panpan Xu, Yuan, X. and Qu, H., 2013. Edge bundling in information visualization. *Tsinghua Science and Technology*, 18(2), pp.145–156. https://doi.org/10.1109/TST.2013.6509098.

Zhou, J., Corcoran, J. and Borsellino, R., 2017. Mapping cities by transit riders' trajectories: The case of Brisbane, Australia. *Environment and Planning A: Economy and Space*, 49(8), pp.1707–1709. https://doi.org/10.1177/0308518X17702647.

Zhou, Z., Meng, L., Tang, C., Zhao, Y., Guo, Z., Hu, M. and Chen, W., 2019. Visual Abstraction of Large Scale Geospatial Origin-Destination Movement Data. *IEEE Transactions on Visualization and Computer Graphics*, 25(1), pp.43–53. https://doi.org/10.1109/TVCG.2018.2864503.

Zinsmaier, M., Brandes, U., Deussen, O. and Strobelt, H., 2012. Interactive Level-of-Detail Rendering of Large Graphs. *IEEE Transactions on Visualization and Computer Graphics*, 18(12), pp.2486–2495. https://doi.org/10.1109/TVCG.2012.238.

Zipf, A., 2002. User-Adaptive Maps for Location-Based Services (LBS) for Tourism. In: K.W. Wöber, A.J. Frew and M. Hitz, eds. *Information and Communication Technologies in Tourism 2002*. [online] Vienna: Springer Vienna.pp.329–338. https://doi.org/10.1007/978-3-7091-6132-6_34.

Appendix A - Usability testing scenario

Introduction

As a transport expert you have access to a growing number of (mobility) data. The data is used to make decisions that improve the accessibility of an area. Visualisation of travel behaviour can help. In order to determine which forms of visualisation best suit the various phases in the decision-making process, you will be asked to read the background information and the task description. Subsequently, you will be asked to perform the subtasks shown on the screen one by one.

Background information

Following the COVID-19 outbreak in the Netherlands in March 2020, movement behaviour has changed dramatically. The government has called on the population to work from home as much as possible and to travel as little as possible. Events have been cancelled, shopping has been discouraged and at certain times museums, bars and restaurants have been closed. This has led to an average decrease in traffic volume of 17% on the main road network in the first three quarters of 2020. Over the same period, the number of passenger kilometres travelled by public transport (bus, tram, metro and train) fell by at least 38.5%. The number of bicycle rides has remained more or less the same (Bakker, 2020). However, there has been a shift from home-work and home-study trips to more recreational and longer cycling trips. The number of trips in the morning and evening rush hour has decreased considerably. The Knowledge Institute for Mobility Policy indicates that the traffic volume decreased by 30% during rush hours (Bakker, 2020).

Besides the above-mentioned situation, there are several developments that affect people's travel behaviour:

- Construction of new dwellings - By 2030, the government wants 845,000 new homes to be built in the Netherlands (DGBRW Directie Woningmarkt, 2020). The city of Rotterdam has the ambition to have 50,000 new homes built by 2040 (Gemeente Rotterdam, 2019).
- Infrastructural projects - The impact of the extension of the motor roads A16 to the A13, the Blankenburg connection or new express cycle routes.
- The increase in the supply and use of bicycle, scooter and car sharing systems.
- An increase in sales of electric bikes by 2020. Pedelecs enable people to travel longer distances more quickly. More destinations come within reach.
- Implementation of the maximum speed of 30 km per hour in built-up areas.
- Mobility concepts, up-to-date information and alternative forms of transport - such as Mobility As A service, real time travel and traffic information, web applications or electric scooters.

Bases on the above information, the transport authority is asking transport experts to draw up a mobility plan for the Rotterdam region for the next five years. The aim of this plan is to keep the region accessible even after COVID-19 through the most efficient, effective and sustainable forms of transport and infrastructural interventions.

Task description

Because this is a complex issue, this assignment focuses on only one of the preconditions for the successful execution of a mobility study: the efficient, effective and satisfactory interpretation of movement data using flow maps. A flow map is a thematic map that depicts on a map movements of objects, natural phenomena, data, ideas, people or animals between the location of origin and destination. In addition, for the purpose of clarity, the geographical area in this study has been demarcated to the area within the ring road of Rotterdam.

As a policymaker, you are asked to assess a set of different flow maps and symbology on usability and applicability for drawing up a mobility plan. While consulting and applying the geographical information, you will be asked to think out loud. Explain in your own words what you perceive and why you can or cannot use a visualisation when making a decision. Which visualisations and symbols help you in which phase of your decision-making? Why are certain symbols clear and others unclear? Why are certain symbols suitable for this task and others not? With every map you look at for the first time, take the time to absorb it and share your first impression.

Note of attention

The visualisations shown are prototypes and do not contain all the available and correct data. The execution of the assignment is about how movement data are visualised and not about the exact truth. To prevent learning effects, the data in each visualisation changes.

Appendix B - Interview tasks

Task no.	Visual stimuli	Task	Expected response	Max. time	Score	Points of attention
I1	Online reference map of service area of RET scale 1:47.500 (see appendix D)	Draw a circle on the map around the municipalities below: A - Ridderkerk B - Vlaardingen	Respondent knows where the municipality is on the map and circles it correctly.	3 min.	1 point for each correctly drawn circle	Is the respondent very specific and detailed or coarse and inaccurate?
I2	Online reference map of service area of RET scale 1:47.500 (see appendix D)	Mark the exact location of transit hubs on the map with a letter: C - Alexander D - Schiedam Centrum E - Zuidplein	Respondent knows where the hubs are on the map and mark them correctly.	2 min.	1 point for each correctly drawn hub	How accurate does the subject mark the locations?
I3	Online reference map of service area of RET scale 1:47.500 (see appendix D)	Draw a circle on the map around the neighbourhoods of: F - Kralingen G - Pernis	Respondent knows where the neighbourhood is on the map and circles it correctly.	3 min.	1 point for each correctly drawn border	Is the respondent very specific and detailed or coarse and inaccurate?
I4	Online reference map of service area of RET scale 1:47.500 (see appendix D)	Draw the exact line on the map with a colour: Metro line C - red	The respondent knows how the line runs through the city and draws it correctly.	4 min.	1 to 3 points for a correctly drawn line	How accurate does the subject draw the line on the map?
I5	Online reference map of service area of RET scale 1:47.500 (see appendix D)	Draw a line between the neighbourhoods where the largest flow of travellers (car, bicycle, public transport) takes place on an average working day. Do this for the three largest origin - destination flows.	The respondent knows between which areas the largest flow of travellers pass.	5 min.	3 points for a correctly drawn edge	How does the respondent visualise the edges between areas? Where does the candidate position the centroids per area?

Question no.	Question	Max. time	Points of attention
I6	Write a proposal to connect a new neighbourhood with 4,000 inhabitants to a metro station that is on average 2,500 metres away. Which steps do you follow in the decision-making process to arrive at your choice of means of transport or a mix of them, the routes, stops and facilities? What information should be shown on the map you have just used so that you can determine the most effective route for a line that makes an area more accessible?	5 min.	Which phases does the respondent distinguish?
I7	How should this information be visualised?	3 min.	

Appendix C - Usability tasks

The complete online usability test is available (in Dutch):
https://flowmap.fra1.digitaloceanspaces.com/research/flowmap_0.html

Task no.	Question / Task	Symbology	Points of attention
Flowmap_0	Select the flow map that most clearly shows where the most movements take place, why?	Straight, curved and bundled edges.	Does the participant prefer straight, curved or bundled edges?
Flowmap_1	Click with your mouse on the two neighbourhoods with the highest number of movements.	Straight edges with various line thicknesses, gradient and arrowhead with an angled side on one side, pie chart node.	Can the participant distinguish the line thicknesses without a legend? What influence does symbology and overlap have?
Flowmap_2	Indicate on the map with your mouse between which neighbourhoods the least number of journeys take place.	Straight edges with gradient and arrowhead with an angled side on one side, pie chart node and legend.	Can the participant distinguish the line thicknesses with a legend? What influence does symbology and overlap have?
Flowmap_3	Click with your mouse on the edges that differ between period 1 and period 2	Straight edges with various line thicknesses, gradient and arrowhead with an angled side on one side, pie chart node.	How quickly can participants correctly distinguish the differences between edges?
Flowmap_4	Click with your mouse on an arrow between which the third largest number of movements takes place.	Curved edges with various line thicknesses, gradient and arrowhead, pie chart node.	Can the participant distinguish the line thicknesses without a legend? What influence does symbology and overlap have?

Flowmap_5	Click with your mouse on an edge that represents more than 1,501 and less than 2,250 movements.	Curved edges with gradient and arrowhead, pie chart node and legend.	Can the participant distinguish the line thicknesses with a legend? What influence do symbology and curvature have in the edge?
Flowmap_6	Between which neighbourhoods in Rotterdam South do the third largest number of trips take place? Click on the edge(s).	Coloured curved edges with a single line width, arrowhead and graphical icon node.	Can the participant distinguish the line colours without a legend? Is the participant able to identify the data classes to the different colours in the flow map?
Flowmap_7	Click with your mouse on a flow in the Feijenoord neighbourhood with less than 1,501 movements.	Coloured curved edges with a single line width, arrowhead, graphical icon node and legend.	Can the participant distinguish the line colours in the flow map and legend?
Flowmap_8	Click with your mouse on the edges that differ between period 1 and period 2. You have 1 minute for this task.	Coloured curved edges with a single line width, arrowhead and graphical icon node.	How quickly can participants correctly distinguish the differences between edges? What influence does time pressure have on the participant?
Flowmap_9	Click with your mouse on the neighbourhoods with the highest number of movements.	Coloured straight edges with a single line width, arrowhead and graphical icon node.	Can the participant distinguish the line colours without a legend? Is the participant able to identify the data classes to the different colours in the flow map?
Flowmap_10	With your mouse, click the neighbourhoods where the total number of trips to the area is greater than the number of trips from the area. You have 1 minute for this task.	Coloured straight edges with a single line width, arrowhead, graphical icon node and legend.	How quickly can participants correctly distinguish the differences between neighbourhoods? Does the subject use the edges or the nodes to perform the task? What influence does time pressure have on the participant?

Flowmap_11	How many trips depart from the Stadsdriehoek (city centre) neighbourhood in a westward direction within 1 kilometre?	Flow map with wind rose diagram node. Wind rose shows for 12 directions and three distance classes the number of movements from the area. Edges with even colour hue and whole arrow. Legend explains wind rose segments.	Can a participant interpret and apply a complex node?
Flowmap_12	Click with your mouse on the edges that differ between period 1 and period 2.	Coloured straight edges with a single line width, arrowhead and graphical icon node.	How quickly can participants correctly distinguish the differences between edges?
Flowmap_13	Click with your mouse on the area that has the least number of movements between 12:00 and 18:00	Pie chart node with four quadrants in different hues. Each quadrant represents a time period of six hours. Edges with even colour hue and whole arrow. Legend explains quadrants.	Can a participant interpret and apply a complex node?
Flowmap_17	Click on the tram segment where the performance between two stops decreases the most.	Line network map with line segments between stops. For each line segment, a hue indicates whether the return is more or less positive.	Can the subject distinguish different colour hues and line thicknesses? What logic does the subject use in ranking the performance of a public transport line or segment between two stops.

Flowmap_18	You notice two different visualisation that show the occupancy between stops: schematic and geographical. Which visualisation offers the most information? Which visualisation to use in which situation?	Schematic map of two tram lines. Each line has a separate colour. Stops including stop names. Geographical map shows both tramlines with a separate colour, including stops and stop names in a dark grey base map. The occupancy between stops is represented in both maps by a line width.	What is a participant's preference in terms of map type? Why? How does the subject apply the chosen map?
Flowmap_19	When and how do you use the following levels of detail?	Dark grey base map with tramline network. Performance tramline network is shown in colours. Three different scale levels are shown: complete service area, city and neighbourhood level.	Which participant uses a specific scale level at which moment and for which application? Which information should be shown on the map at which scale level?
Flowmap_20	Click on the line segment where the number of bus passengers increases the most during rain, while car ownership is highest there.	Animated map with car ownership represented by coloured polygons (static), light grey base map, animated bus line segments based on occupancy over time represented by line thickness and animated rain cloud object.	How does a participant deal with a complex flow map in which several variables change over time?

Flowmap_21	Click on the bus route where the traffic flow is worst. What alternative route is feasible based on the map?	Light grey base map. Road network with the traffic speed per segment displayed in four colours explained in a legend. Bus routes shown in a separate hue.	Is the participant able to identify traffic bottlenecks in the map? Can the subject identify alternative solutions using the symbology shown in the map?
Flowmap_23	From which neighbourhoods do people travel to the Feyenoord area?	Straight edges with gradient and arrowhead with an angled side on one side, pie chart node and legend.	Can the participant distinguish the line thicknesses without a legend? What influence does symbology and overlap have?
Flowmap_24	How many distinct classes of values do you observe in the flow map?	Curved edges with various line thicknesses, gradient and arrowhead, pie chart node.	Is the participant able to identify the right number of classes?
Flowmap_25	The map below shows the 100 largest flows (car, bicycle and public transport) for one day within the motor ring of Rotterdam. How can you use this information to improve the timetable or the public transport network?	Curved edges with various line thicknesses, gradient and arrowhead, pie chart node.	How does a participant apply the information on a flow map to improve public transport?
D1_blue_ flow_map	How can you use the map below and the functions offered to improve the public transport network?	Web based dynamic flow map shows 40.000 movements to and from the service area. Menu offers the possibility of selecting edge colour, node form, aggregation and filtering functions.	How can a participant apply a dynamic flow map to base mobility decisions on? Which functions and information should the dynamic flow map offer?

D2_dynamic_ flow_map	How can you use the map below and the functions offered to improve the public transport network?	Web based dynamic flow map shows 100 biggest movements within the service area. The flow map offers functions to select total flows, bi-direct flows. Flow map includes a separate layer with social demographic information.	How can a participant apply a dynamic flow map to base mobility decisions on? Which functions and information should the dynamic flow map offer?

Appendix D - Post-test questionnaire questions

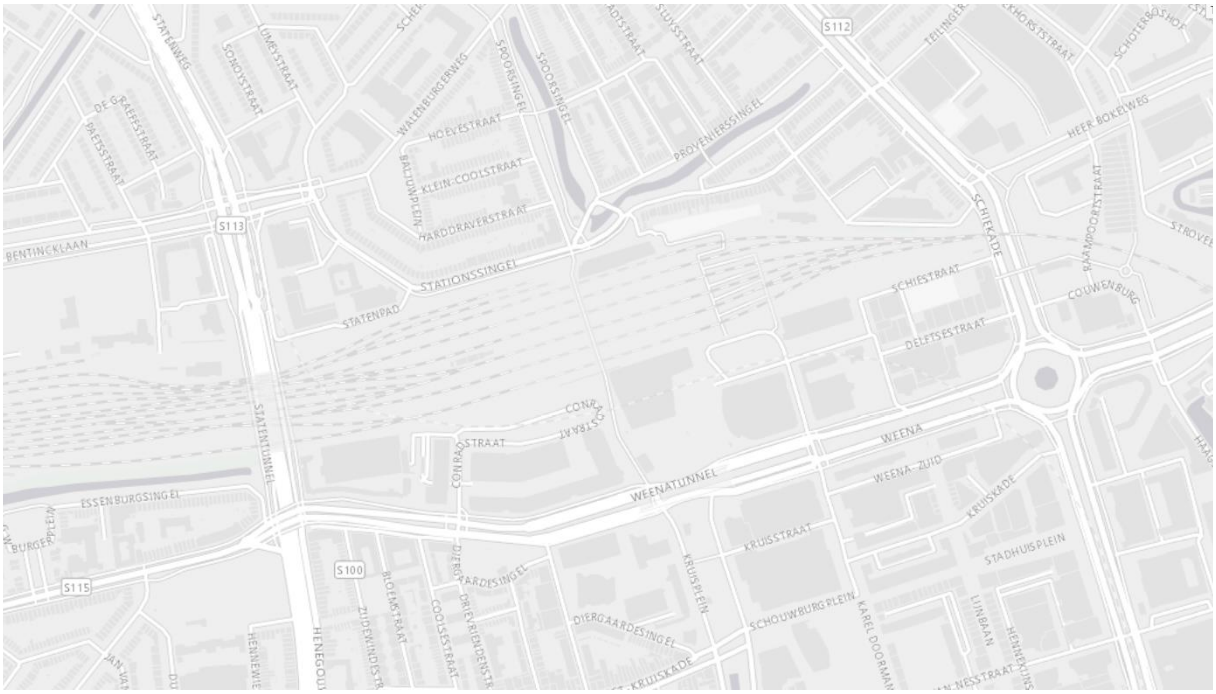
Question no.	Question	Options	Points of attention
Flowmap_35	Select the base map you would use to determine where most people travel (yellow line = few travellers, red line = many travellers), why?	- Topographic base map with yellow and red edges - Dark grey base map with yellow and red edges - Satellite base map with yellow and red edges - Light grey base map with yellow and red edges	Which type of base map is best for the participant to read, interpret and analyse the flow map? What information should be depicted on the base map in order to orient yourself properly?
Flowmap_36	What type of edge(s) most clearly indicate origin, destination, and value? Why?	- Straight edges with various line thicknesses, gradient and arrowhead with an angled side on one side, pie chart node - Curved edges with various line thicknesses, gradient and arrowhead, pie chart node - Coloured curved edges with a single line width, arrowhead and graphical icon node - Coloured straight edges with a single line width, arrowhead and graphical icon node - Combined edge and arrowhead with one hue and pie chart node - Divided edge with for each modality and direction a separate hue including an arrowhead. Pie chart with coloured segment per incoming and outgoing modality.	How do the participants assess the different symbology variants in relation to each other? What are the advantages and disadvantages?
Flowmap_37	What insights into movement behaviour do the node symbols below provide?	- Graphical icon node - Pie chart node - Wind rose diagram node - Pie chart with four quadrants	How can a participant apply the node symbology shown? What are the advantages and disadvantages?

Flowmap_38	Click on the thinnest line with the arrow where you can still read the value of the line thickness.	Edge with arrow 0.25, 0.5, 1, 1.5, 2, 2.5, 3, 3.5 pixels	What is still legible for the participant?
Flowmap_39	For each node type, click on the smallest point symbol that you can still see clearly and whose values you can read off.	Four node symbol variants and five different sizes: wind rose diagram node, pie chart, pie chart with quadrants and graphical icon node.	What is still legible for the participant?
Flowmap_40	What information should be shown on the map in order to make the right decision about the location of a new public transport stop?	Openstreetmap. Options: Public transport lines and existing stops, Number of passengers embarking and disembarking, Frequency per line, Traffic flows per modality, Population density, Infrastructure and Other, namely.	Which map layers with social-demographic, economic and infrastructural information do they need in order to make mobility decisions?
Flowmap_41	How attractive do you find the following map image?	Flow map with coloured curved edges and graphical icon nodes. Options: Very attractive, Attractive, Neutral, Unattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?
Flowmap_42	How attractive do you find the following map image?	Flow map with curved edges with various line thicknesses, gradient and arrowhead, pie chart nodes. Options: Very attractive, Attractive, Neutral, nattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?
Flowmap_43	How attractive do you find the following map image?	Flow map with combined edges with two arrowheads, pie chart nodes. Options: Very attractive, Attractive, Neutral, Unattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?

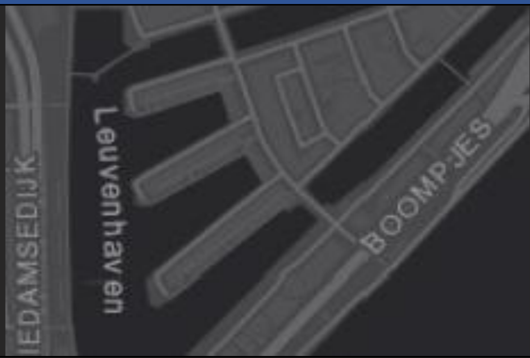
Flowmap_44	How attractive do you find the following map image?	Flow map with straight edges with various line thicknesses, gradient and arrowhead with an angled side on one side, pie chart nodes. Options: Very attractive, Attractive, Neutral, Unattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?
Flowmap_45	How attractive do you find the following map image?	Flow map with coloured straight edges with a single line width, arrowhead and graphical icon nodes. Options: Very attractive, Attractive, Neutral, Unattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?
Flowmap_46	How attractive do you find the following map image?	Flow map with coloured split curved edges with arrowhead and pie chart nodes. Options: Very attractive, Attractive, Neutral, Unattractive, Very unattractive	Determine to what extent the participant will make use of the presented flow map and symbology. Does the assessment correspond to the input from the usability test?
Flowmap_47	How important is the legend for explaining the elements in the map?	Straight edges with gradient and arrowhead with an angled side on one side, pie chart node and legend. Options: Very important, Important, Not important / not unimportant, Unimportant, Not at all important	Why do participants find it important that the legend is shown in or with the map?
Flowmap_48	Labels in the map with neighbourhood names are essential for orientation.	Flow map with combined coloured curved edges with two arrowheads and pie chart nodes. Dark grey base map with neighbourhood borders and labels with the neighbourhood names. Options: Fully disagree, Disagree, Do not agree / do not disagree, Agree, Fully Agree	Why do participants think it is important to have labels of important landmarks, destinations or neighbourhoods in the map?

Flowmap_49	I believe it is easy to observe the differences in traveller flows between time periods.	Flow map with coloured curved edges and graphical icon nodes. Options: Fully disagree, Disagree, Do not agree / do not disagree, Agree, Fully Agree	How easy or difficult does the respondent perceive the differences between different periods for a certain type of symbology.
Flowmap_50	Which form of visualisation do you prefer?	2D flow map and 3D flow map	Why does the participant prefer a 2D flow map or a 3D flow map?
Flow_map_51	When do you use a static flow map and when do you use a dynamic flow map?	Example of a static flow map and an example of dynamic flow map.	Finding out why participants prefer to use a static flow map or a dynamic flow map.
Flow_map_52	Personal details	- Job description - Number of years' experience in the public transport or mobility sector - How and where do you use maps or navigation systems (work / private)? - What kind of screen do you use for this user research (laptop, external screen)? - Do you use glasses or contact lenses? - Education - Age	The gender of the participant is also registered. Personal data is recorded to determine whether there is a relationship with performance, preferences, geographical knowledge and knowledge of the public transport network.

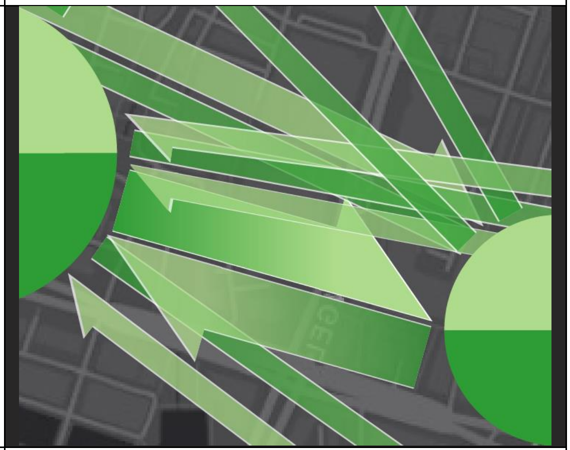
Appendix E - Map of the service area of RET
(scale 1:47.500 - variable zoom)



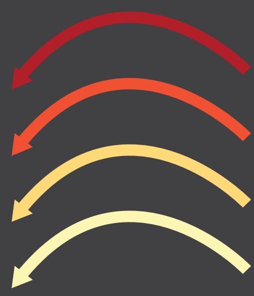
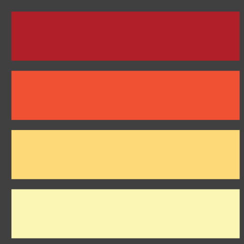
Appendix F - Flow map design variants

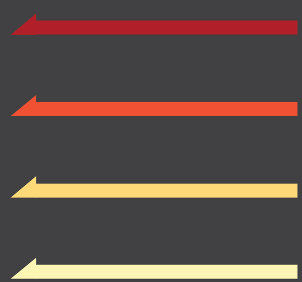
Flow map element	Properties	Visual
Reference map	Dark Grey Canvas Base (WGS84) (Esri, 2020) Scale - Fixed 1:24.000	
Additional map layers	Neighbourhoods within Rotterdam's ring road	
Map extent	Longitude 4.346596, Latitude 51.852409 - Longitude 4.593272, Latitude 51.957894	

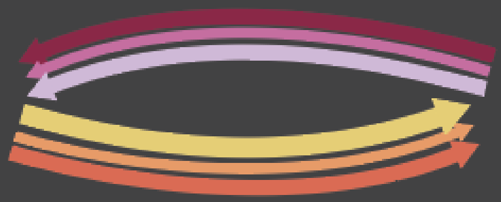
Type of edge	Straight • Gradient colour fill • Variable line width • Arrowhead with an angled side on one side • White outline 0.38 pixels	
	Movement intensity is visualised through a variable thickness based on four different data classes (6.6 pixels, 9.5 pixels, 12.5 pixels and 15 pixels)	

	Gradient colour fill - outgoing movement flow (HEX #33a02c) to incoming movement flow (HEX #b2df8a)	
	In order to distinguish overlapping edges, a white stroke has been added and the overlapping edges have an opacity of 75%.	
Type of arrowhead	Arrowhead with an angled side on one side to save space when placing edges against each other.	

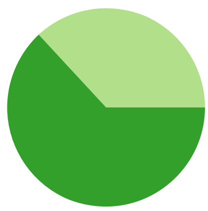
Type of edge	Curved Gradient colour fill Variable line width Full arrowhead	
	Movement intensity is visualised through a variable thickness based on four different data classes (5.83 pixels, 8.75 pixels, 11.67 pixels, 14.58 pixels)	
	Gradient colour fill - outgoing movement flow (HEX #33a02c) to incoming movement flow (HEX #b2df8a)	
Type of arrowhead	Arrow 7 - Adobe Illustrator 2021	

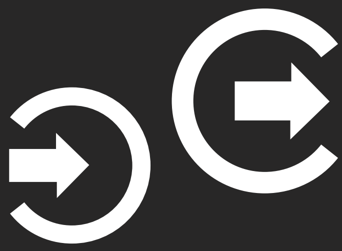
Type of edge	Curved • Solid hue • Fixed line width 3 pixels • Full arrowhead	
	Movement intensity is visualised through an identical line thickness but using a distinctive colour based on four different data classes. The applied hue is related to the amount of movements. Light yellow = few movements. Dark red = many movements.	
	Colour hues HEX #b11f29 HEX #f05132 HEX #fed977 HEX #fcf6b4	
Type of arrowhead	Arrow 7 – Adobe Illustrator 2021	

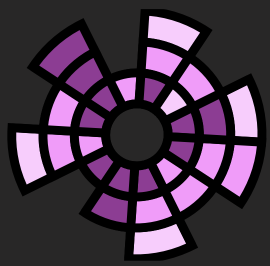
Type of edge	Straight • Solid hue • Fixed line width 3 pixels • Full arrowhead	
	Movement intensity is visualised through an identical line thickness but using a distinctive colour based on four different data classes. The applied hue is related to the amount of movements. Light yellow = few movements. Dark red = many movements. Properties are identical to the curved version.	

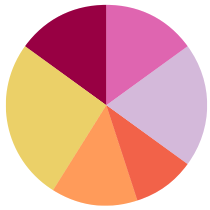
Type of edge	Curved • Edges divided by modality • Each direction and modality has its own hue • Line thickness depends on volume with movements • Full arrowhead	
	Colour hues HEX #981446 HEX #D468A5 HEX #D4BADB HEX #EACF67 HEX # F4995D HEX # EC624B	

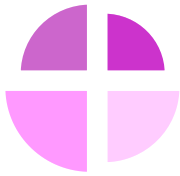
Type of edge	Curved • Combined incoming and outgoing flow • Solid hue #ffffff • Full arrowhead	

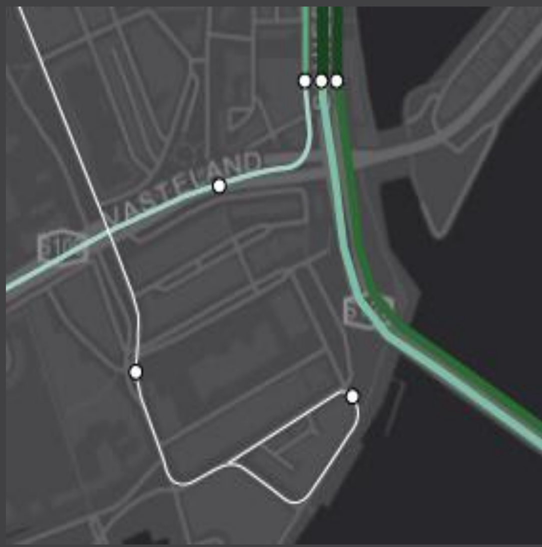
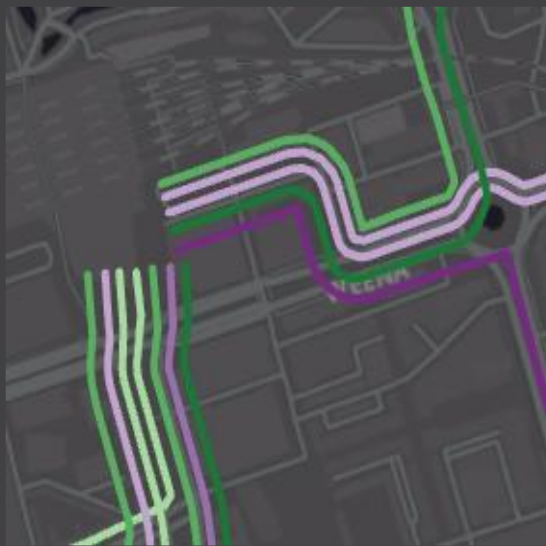
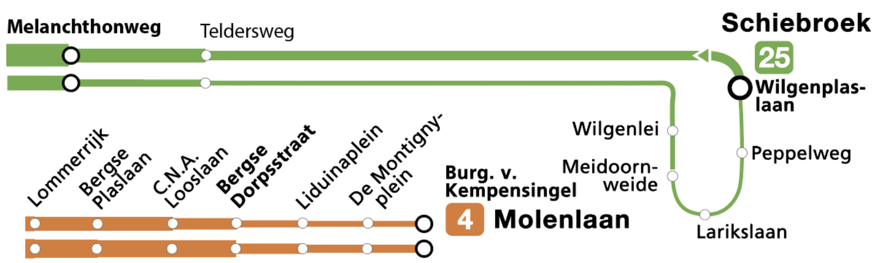
Flow map element	**Properties**	**Visual**
Type of node	Pie chart node • Total incoming and outgoing flow for each neighbourhood • Diameter pie chart represents a total volume of movements • Incoming flow HEX #b2df8a • Outgoing flow HEX #33a02c • Edge gradient corresponds to colours in the node	

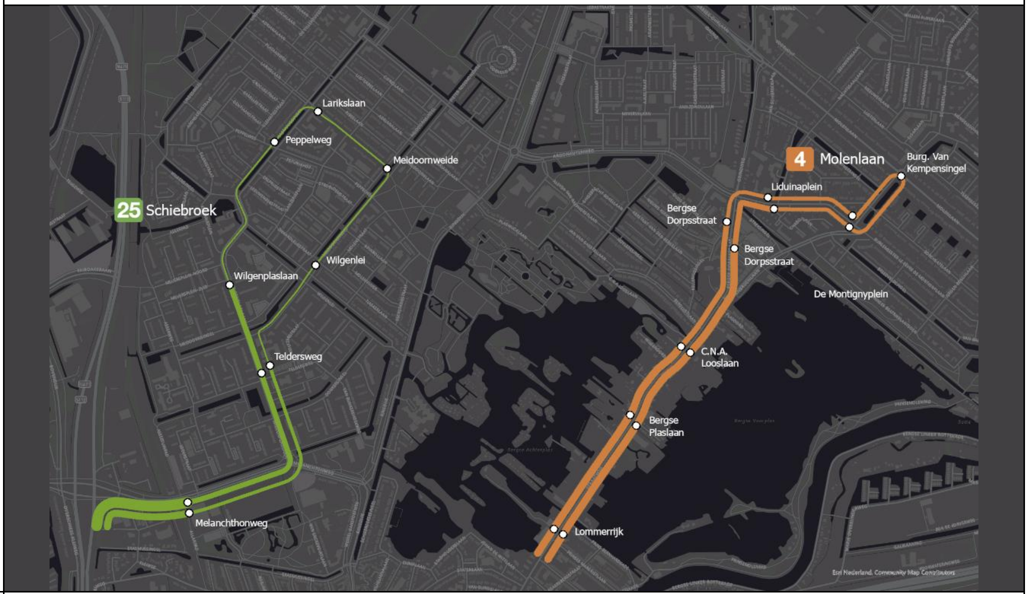
Type of node	Graphical icon node • Incoming and outgoing flows depicted through an arrowhead for each neighbourhood. • Diameter icon represents a total volume of movements • Icon colour HEX #ffffff	

Type of node	Wind rose diagram node • Outgoing flow volumes in distance in twelve directions • Three rings depict distance classes: <= 1.000 M (metres) 1.001 - <= 2.500 M > 2.500 M • Diameter wind rose diagram represents a total volume of outgoing movements • Movement volumes classes are depicted in three different hues: < 1.500 HEX #f7cdfc 1.500 – 3.000 HEX #ff99ff > 3.000 HEX #ff99ff	

Type of node	Pie chart node • Total incoming and outgoing flow for each modality and neighbourhood • Diameter pie chart represents total volume of movements • The market share per modal split and per direction is shown in segments in its own colour according to the corresponding edges: HEX #981446 HEX #D468A5 HEX #D4BADB HEX #EACF67 HEX # F4995D HEX # EC624B	

Type of node	Pie chart with four quadrants • Total incoming flow for each six-hour period and neighbourhood • Diameter pie chart and segments represent a total volume of movements • The total volume of incoming movements per six-hour period is depicted in a segment with separate hue: HEX # cc33cc HEX # ffccff HEX # ff99ff HEX # cc66cc and a white outline around the segment. •	

Map elements	Proportions	Visual
Type of edge	Line segments • Edge width depends on occupancy rate • Solid colour hue per class • Line width per volume of movements 0.5 pixel, 1 pixel, 2 pixels Colour hues: HEX #ffffff HEX #cde7e3 HEX #6bbfa3 HEX #40af76 HEX #006e32 HEX #094420	
	Line segments • Edge colour depends on performance • Solid colour hue per class • Fixed line width 1 pixel Colour hues HEX #a6dba0 HEX #5aae61 HEX #1b7837 HEX #c2a5cf HEX #9970ab HEX #762a83	
Schematic map	Line segments • Solid colour hue per tramline (HEX # 7baa55 and HEX # d07f43) • Line thickness depends on occupancy rate • Optional: arrowhead depicts direction	
		

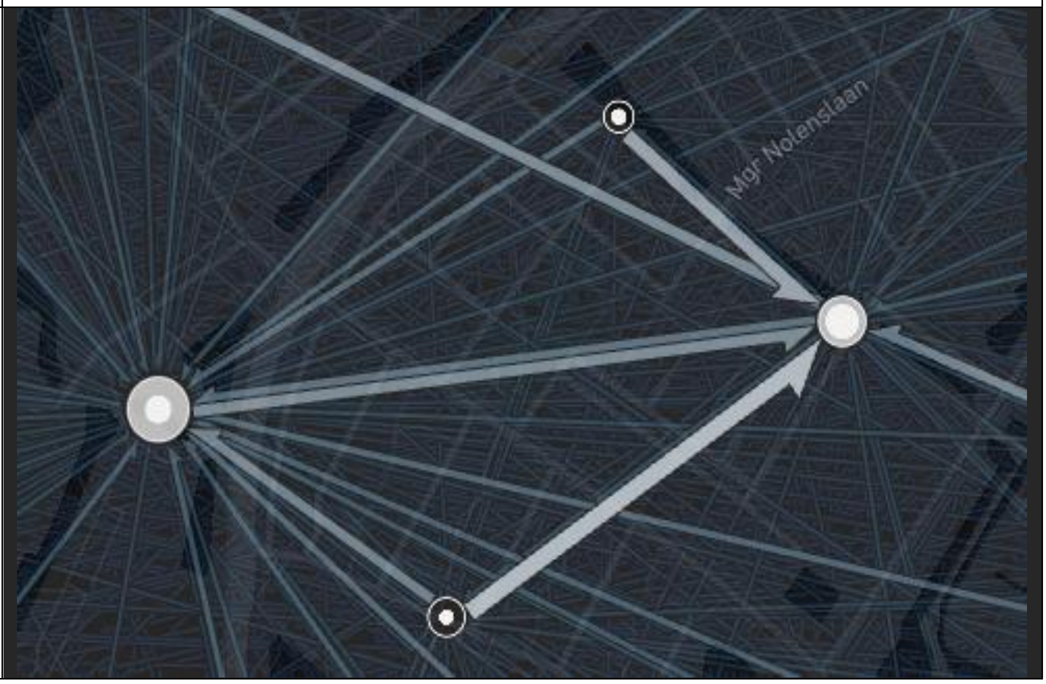
<table>
<tr>
<td rowspan="2">Geographical map</td>
<td>Line segments
• Solid colour hue per tram line (HEX # 7baa55 and HEX # d07f43)
• Line thickness depends on occupancy rate
• Base map dark grey canvas</td>
</tr>
<tr>
<td>
</td>
</tr>
<tr>
<td rowspan="2">Animated map</td>
<td>Line segments
• Solid colour hue bus lines (HEX # 67114b)
• Line thickness depends on occupancy rate

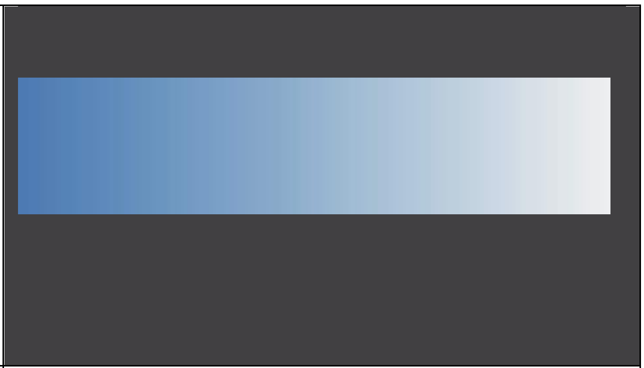
Polygons
• Car ownership in five classes (HEX # e2fdf8, HEX # d5ece5, HEX # 7dc1a7, HEX # 44884c, HEX # 1a441d)

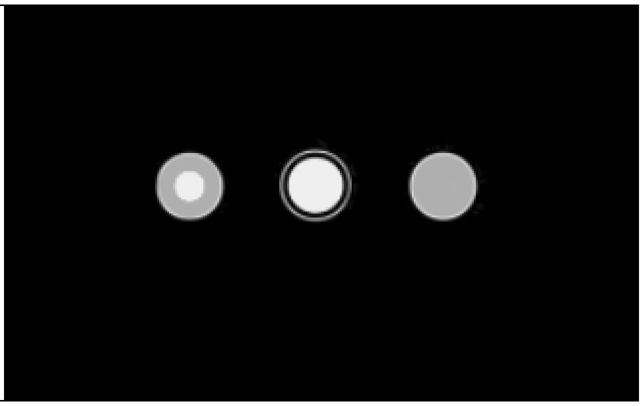
Animated element
• Rain cloud (HEX #336699 40% opacity, HEX #336699 65% opacity)

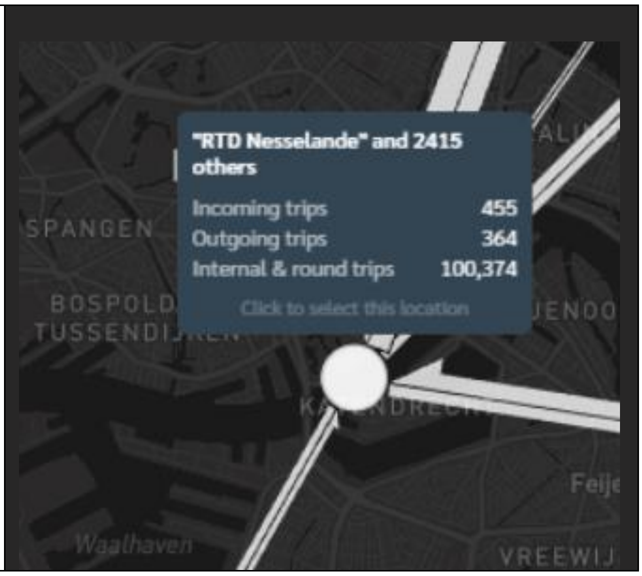
Base map light grey</td>
</tr>
<tr>
<td></td>
</tr>
</table>

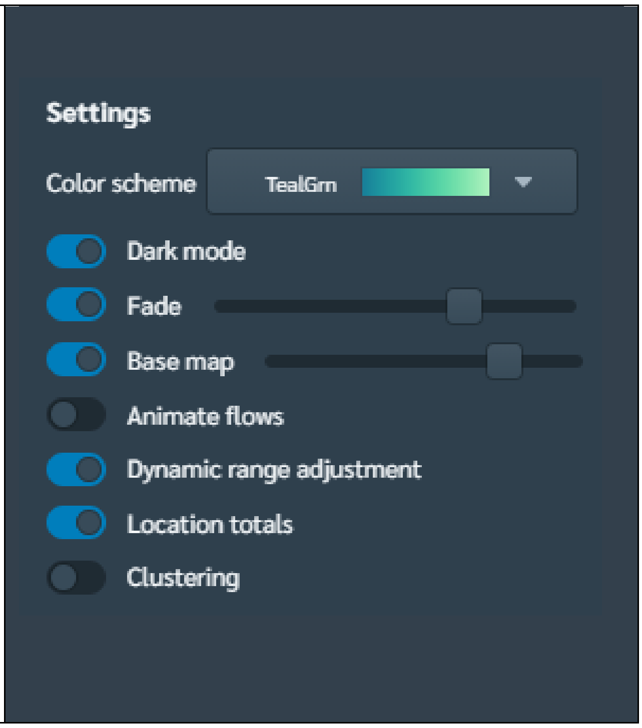
<table>
<tr>
<td rowspan="2">Road network</td>
<td>Line segments
• Solid colour hue per speed segment (HEX # b72619, HEX # f3ae3d, HEX # ffff54, HEX # 61d43f) and bus route (HEX # e0b4e9)
• Line colour hue depends on traffic speed
• Base map light grey</td>
</tr>
<tr>
<td></td>
</tr>
</table>

Type of map	Dynamic / Interactive	
Dynamic map	Online version of the flow map is available: https://tinyurl.com/flowmap1	
Scale	dynamic	
Reference map	OpenStreetMap | MapBox Dark mode (WGS84)	
Map extent	Focus on Longitude 4.346596, Latitude 51.852409 - Longitude 4.593272, Latitude 51.957894	
Type of edge	Straight Movement intensity is visualised through edges with a variable thickness based on the number of movements. Flows representing a higher number of movements are depicted in a lighter hue.	
		

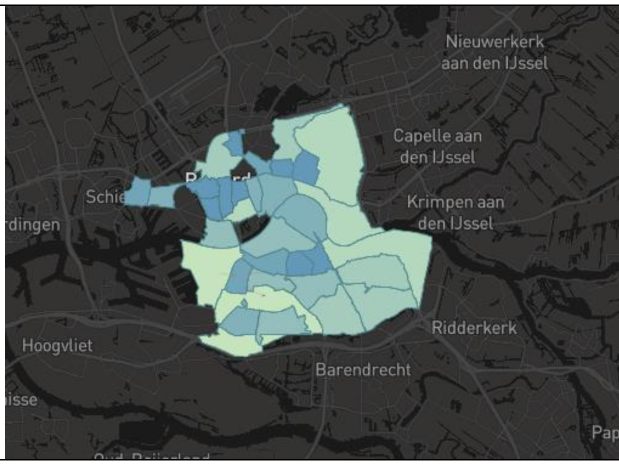
	Colour fills Depending on the volume, edge colours varying from HEX # 3b7cb9 to #ffffff Colours can be adjusted through an online menu. Transparency is applied to distinguish overlapping edges.	
Type of arrowhead	Arrowhead with an angled side on one side to save space when placing edges against each other.	

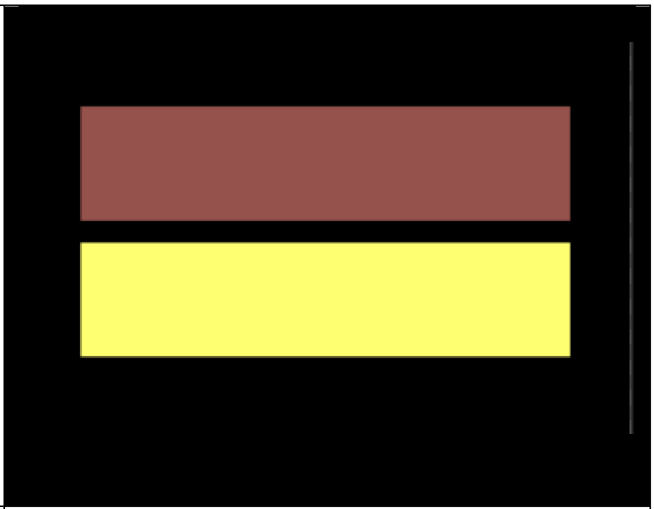
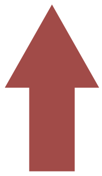
Type of node	Three different graphic symbols represent whether the number of incoming and outgoing passengers is equal, the number of incoming passengers is greater than the number of outgoing passengers or vice versa. The size of the circle visualises the total movement to and from a neighbourhood.	

Interactivity	The interactive flow map is based on technology developed by Ilya Boyandin (Boyandin, 2020) using flowmap.gl, deck.gl, MapBox, d3, blueprint and CARTOColors. Nodes and edges can be clicked to display the values in a pop-up.	

	The map reader can zoom in on the map to get more detail in the base map. Clicking on a node filters the data and shows only the flows to and from the selected neighbourhood. In a drop-down menu, the user can change the reference map, set the transparency, activate an animation or filter the incoming or outgoing movement flows. The animation shows the direction and intensity of movement behaviour between neighbourhoods through the line thickness and a moving edge towards an area.	

Type of map	**Dynamic / Interactive**	
Dynamic map	Online version of the flow map is available: https://tinyurl.com/flowmap2	
Scale	dynamic	
Reference map	OpenStreetMap | MapBox Dark mode (WGS84)	

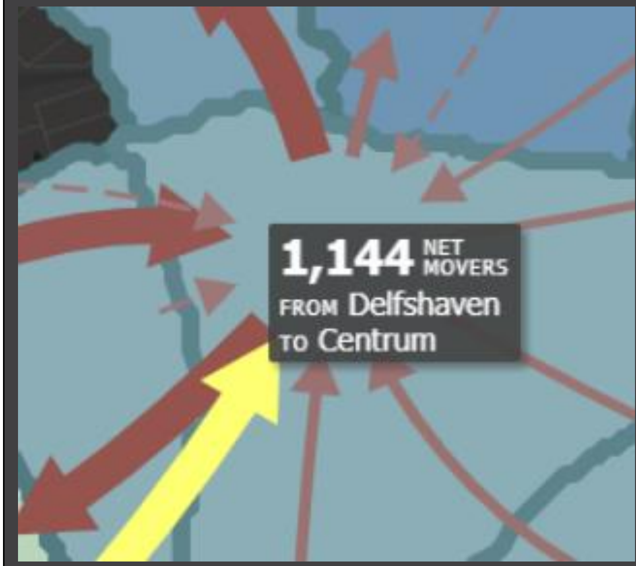
Additional map layers	Social-demographic information: population destination per km².	
Map extent	Focus on Longitude 4.346596, Latitude 51.852409 - Longitude 4.593272, Latitude 51.957894	
Type of edge	Curved Movement intensity is visualised through edges with a variable thickness based on the number of movements. Flows representing a higher number of movements are depicted with a solid edge. Flows with a small number of movements are shown in dotted lines.	
		

	Colour hue HEX #a14b47 Selected edge HEX #ffff54	
Type of arrowhead	Arrowhead with an angled side on one side to save space when placing edges against each other.	
Type of node	No physical node is displayed. The arrangement of the edges and arrows form an open node. Depending on the total amount of movement, the open space becomes larger or smaller.	
		

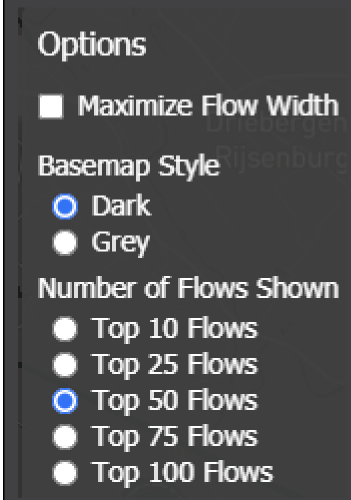
<table>
<tr>
<td>Interactivity</td>
<td>The interactive flow map is based on technology developed by Daniel M. Stephan (2018) using D3.js and html.

Edges can be clicked to display the values in a pop-up.

Separate radio buttons allow the map reader to display the number of flows shown. Buttons give the user the possibility to show edges only for the total flow between neighbourhoods or the difference in the incoming and outgoing direction. When a map reader clicks on an area, only the flows to and from the neighbourhood are shown.</td>
<td>



</td>
</tr>
<tr>
<td></td>
<td>The user can zoom in on the flow map and select the number of the largest flows to be shown.</td>
<td>



</td>
</tr>
</table>

Appendix G - Participants

	R1	R2	R3	R4	R5	R6	R7
Gender	Female	Male	Male	Male	Male	Female	Female
Age	22	21	31	43	61	50	33
Education	HBO	HBO	HBO	WO	HBO	WO	WO
Glasses / contact lenses	None	Glasses	None	None	Glasses (small deviation red / brown)	Glasses	None
Screen type	Desktop 24"	Desktop 24"	Desktop	Desktop	Desktop	Laptop	Laptop
Use of maps	Google maps on mobile	Google maps on mobile	Satellite maps, Google map, Streetview, GeoHastus, OV-lite	OSM walking, mobile maps.me, GeoHastus, Google Maps	Atlases	Car navigation, paper maps	Route planning motor cycle, Google maps, satellite map
Experience in mobility	3 months	3 months	10 years	15 years	35 years	15 years	4 years
Job description	Trainee	Trainee	Transport Expert	Transport Expert	Policy advisor transport	Product manager travel information	Transport expert

	R8	R9	R10	R11	R12	R13
Gender	Male	Male	Female	Male	Male	Male
Age	48	58	45	51	57	54
Education	WO	HBO	WO	WO	HBO	WO
Glasses / contact lenses	Contact lenses	Glasses. Do not use glasses at the computer. Reduced vision.	Glasses. Do not use glasses at the computer.	Contact lenses	Glasses	Glasses (Colour Blindness)
Screen type	Laptop	Desktop	Laptop	Laptop	Laptop	Laptop
Use of maps	Google maps, network maps, ANWB, Falk plan, wiring diagram	GeoHastus, Google Maps, Street view, OV-lite, Garmin	Digital maps for bicycle and walking routes	Waze, Flitsmeister	Route planning on mobile	Collect paper transport maps, walking maps, atlases
Experience in mobility	22 years	39 years	7 years	24 years	12 years	25 years
Job description	Policymaker transport	Transport expert	Manager proposition marketing and marketing communication	Expert data and models	Manager Marketing, Sales and Services	Policymaker transport

Appendix G – Informed consent form

Informed consent

Research title: Cartographic design and usability of flow maps in public transport

Responsible researcher: René Vaartjes

To be completed by the participant

I declare to have been informed in a way that is clear to me about the nature, method and purpose of the research. I know that the data and results of the research will only be disclosed to third parties anonymously and confidentially.

I understand that audio and video material or adaptations thereof will only be used for analysis and/or scientific presentations. I voluntarily agree to participate in this study.

I hereby reserve the right to terminate my participation in this study at any time without giving reasons.

Name of participant: Date and place:

Signature of participant:

To be filled in by the conducting researcher

I have given a verbal explanation of the research. I will answer any remaining questions about the study to the best of my ability. The participant will not suffer any negative consequences from prematurely terminating this study.

Name researcher: René Vaartjes Date and place: 28 February 2021, Rotterdam

Signature researcher: