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Nudging Travelers to Societally Favorable Routes by Means of Cartographic Symbolization

Von der Fakultät für Bauingenieurwesen und Geodäsie

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Abstract

With increasing urbanization, a well-functioning transport infrastructure that takes into account the needs of the society is becoming more and more important. In particular, a high proportion of motorized traffic can cause far-reaching problems that affect large parts of the urban population, such as traffic congestion or increased air pollution. To counteract this trend, an optimized distribution of traffic flows could improve the situation from a societal perspective. Since most routing decisions are made based on digital maps before the journey starts, clear and intuitive visualization is crucial for conveying the cartographic information to the traveler. While most existing services typically provide the most efficient routing options in terms of travel time, newer approaches attempt to guide drivers to *societally favorable* routes. These take into account societally relevant factors, which are referred to as scenarios in this thesis, and include environmental issues such as traffic congestion or air pollution. However, since such a *societally favorable* route is not necessarily efficient for the individual traveler, it is important to convince the traveler to choose a seemingly less efficient route.

For this purpose, an automatic method for visualizing route maps is developed, which calculates *societally favorable* routes, and communicates them visually to the end user in such a way that the user would prefer to use them. For this communication, different visual variables of cartography are used, whose usage is adapted to the different scenarios and controlled by scenario-specific thresholds. Based on the goal of dynamic distribution of traffic flows, the proposed method recommends routes that are not necessarily the shortest or fastest, but rather those that seek to avoid unfavorable or hazardous paths or areas. The proposed design variants of route maps use a large variety of symbolization techniques; including classic visual variables of cartography such as color, size or pattern, but also more abstract methods that use cartographic generalization techniques.

The subjective and objective usability of the proposed symbolization methods is investigated in three different user studies. In a first step, subjective usability is tested by evaluating different sample route map representations in terms of their attractiveness, intuitiveness and suitability for visually communicating route favorability in the *air quality* scenario (*user study 1*). The results of this study indicate that some of the proposed design variants may be suitable for air quality representations. In particular, design variants with variations in the intensity value of color are preferred over more complex visualizations that may combine multiple visual variables. In a further step, objective usability in terms of effectiveness is tested by examining the influence of the applied symbolization on the traveler's route choice decision. In this context, *user study 2* tests the effectiveness of different cartographic design variants based on the *traffic* scenario for nudging travelers towards choosing a longer but less congested route. The results demonstrate that the applied visual modifications contribute to a change in route choice behavior. For most design variants, participants' route choice is significantly influenced towards the *societally favorable* route. *User study 3* compares the effectiveness for influencing route choice in both the *traffic* and *air quality* scenarios. Additionally, this study examines the influence of emotional responses on decision making. The results of this user study confirm that map symbols can be used effectively for influencing route choice toward choosing the favorable route for the two tested scenarios. At the same time, results also show that the appropriateness and effectiveness of the chosen visual communication between the end user and the map may vary depending on the scenario. The results further indicate that for some of the design variants, the emotions felt in response to the map visualization contribute significantly to choosing the *societally favorable* route.

The results of this thesis show that map symbolization can be successfully used for inducing a behavior change in route choice with the aim to achieve a more social behavior in traffic participants. Hence, the findings of this research intend to support map designers or developers of future routing services or navigations systems in their design choices.

Keywords: Cartographic design, visual communication, visual variables, route choice behavior, user study, emotions

Kurzfassung

Mit zunehmender Verstädterung gewinnt eine gut funktionierende Verkehrsinfrastruktur, die den Bedürfnissen der Gesellschaft Rechnung trägt, immer mehr an Bedeutung. Insbesondere ein hoher Anteil an motorisiertem Verkehr kann weitreichende Probleme verursachen, die große Teile der Stadtbevölkerung betreffen, wie z.B. Verkehrsstaus oder erhöhte Luftverschmutzung. Um dieser Entwicklung entgegenzuwirken, könnte eine optimierte Verteilung der Verkehrsströme die Situation für die Gemeinschaft verbessern. Da die meisten Routing-Entscheidungen vor Reiseantritt auf der Grundlage digitaler Karten getroffen werden, ist eine klare und intuitive Visualisierung entscheidend für die Vermittlung kartografischer Informationen an den Reisenden. Während die meisten bestehenden Dienste in der Regel die effizientesten Routing-Optionen im Hinblick auf die Reisezeit bieten, versuchen neuere Ansätze, die Fahrer auf *gesellschaftlich vorteilhafte* Routen zu leiten. Diese berücksichtigen gesellschaftlich relevante Faktoren, die in dieser Arbeit als Szenarien bezeichnet werden. Darunter fallen Umweltprobleme wie Verkehrsstaus oder Luftverschmutzung. Da eine solche *gesellschaftlich vorteilhafte* Route für den einzelnen Reisenden jedoch nicht zwangsläufig effizient ist, ist es wichtig, den Reisenden davon zu überzeugen, eine scheinbar weniger effiziente Route zu wählen.

Dazu wird im Rahmen der Arbeit ein automatisches Verfahren zur Visualisierung von Routenkarten entwickelt, welches *gesellschaftlich vorteilhafte* Routen berechnet und diese so visuell dem Endnutzer kommuniziert, dass dieser sie bevorzugt nutzen möchte. Für diese Kommunikation kommen verschiedene visuelle Variablen der Kartographie zum Einsatz, deren Verwendung auf die verschiedenen Szenarien angepasst sind und über Szenario-spezifische Schwellwerte gesteuert werden. Basierend auf dem Ziel einer dynamischen Verteilung der Verkehrsströme empfiehlt die vorgeschlagene Methode Routen, die nicht unbedingt die kürzesten oder schnellsten sind, sondern vielmehr solche Routen, die ungünstige oder gefährliche Wege oder Bereiche zu vermeiden versuchen. Die vorgeschlagenen Designvarianten von Routenkarten nutzen eine Vielzahl von Symbolisierungstechniken; darunter klassische, visuelle Variablen der Kartographie wie Farbe, Größe oder Muster, aber auch abstraktere Methoden, die kartographische Generalisierungstechniken verwenden.

Die subjektive und objektive Nutzbarkeit der vorgeschlagenen Symbolisierungsmethoden wird in drei verschiedenen Nutzerstudien untersucht. In einem ersten Schritt wird die subjektive Nutzbarkeit getestet, indem verschiedene Beispiel-Routenkartendarstellungen hinsichtlich ihrer Attraktivität, Intuitivität und Eignung zur visuellen und vorteilhaften Kommunikation von Routen im Szenario der *Luftqualität* bewertet werden (*Nutzerstudie 1*). Die Ergebnisse dieser Untersuchung deuten darauf hin, dass einige der vorgeschlagenen Gestaltungsvarianten für die Darstellung von Luftqualität geeignet sein können. Insbesondere werden Gestaltungsvarianten mit Änderungen im Intensitätswert der Farbe gegenüber komplexeren Visualisierungen, die möglicherweise mehrere visuelle Variablen kombinieren, bevorzugt. Im nächsten Schritt wird die objektive Nutzbarkeit im Sinne der Effektivität getestet, indem der Einfluss der verwendeten Symbolisierung auf die Routenwahlentscheidung des Reisenden untersucht wird. In diesem Zusammenhang testet die *Nutzerstudie 2* die Effektivität verschiedener kartographischer Gestaltungsvarianten anhand eines *Verkehrsszenarios*, um Reisende dazu zu bewegen, eine längere, aber weniger überlastete Route zu wählen. Die Ergebnisse belegen, dass die angewandten, visuellen Modifikationen zu einem veränderten Routenwahlverhalten beitragen. Bei den meisten Gestaltungsvarianten wird die Routenwahl der Teilnehmer signifikant in Richtung der *gesellschaftlich vorteilhaften* Route beeinflusst. *Nutzerstudie 3* vergleicht die Effektivität zur Beeinflussung der Routenwahl in den beiden Szenarien *Verkehr* und *Luftqualität*. Zusätzlich untersucht diese Studie den Einfluss emotionaler Reaktionen auf die Entscheidungsfindung. Die Ergebnisse dieser Nutzerstudie bestätigen, dass Kartensymbole effektiv zur Beeinflussung der Routenwahl in Richtung der günstigen Route für die beiden getesteten Szenarien eingesetzt werden können. Gleichzeitig zeigen die Ergebnisse aber auch, dass die Eignung und Wirksamkeit der gewählten, visuellen Kommunikation zwischen Endnutzer und Karte je nach Szenario unterschiedlich ausfallen können. Die Ergebnisse deuten ferner darauf hin, dass bei einigen der Visualisierungsvarianten die Emotionen, die als Reaktion auf die Kartenvisualisierung empfunden werden, wesentlich dazu beitragen, dass von den Nutzern die *gesellschaftlich vorteilhafte* Route gewählt würde.

Die Ergebnisse dieser Arbeit zeigen, dass Kartensymbolisierung erfolgreich eingesetzt werden kann, um eine Verhaltensänderung zu einem sozialeren Verkehrsverhalten bei der Routenwahl zu bewirken. Die Ergebnisse dieser Forschung sollen daher Kartengestalter oder Entwickler zukünftiger Routingdienste oder Navigationssysteme bei ihren Designentscheidungen unterstützen.

Schlagworte: Kartographische Gestaltung, visuelle Kommunikation, visuelle Variablen, Routenwahlverhalten, Nutzerstudie, Emotionen

Contents

1 Introduction

This chapter introduces the motivation of the research carried out as part of this thesis, followed by a description of the problem that is intended to be solved. Afterwards, a description of the research objectives is provided, as well as a set of key hypotheses, which are verified as part of this thesis.

1.1 Motivation and problem statement

As urbanization increases, so does the demand for efficient forms of mobility. In particular, a high proportion of motorized individual transport can cause far-reaching problems for the transport system. Non-optimal distributions of traffic flows can overload parts of the transport infrastructure and lead to problems that can affect the urban population as a whole, such as congestion, traffic safety issues, or health-threatening events including air pollution. In all these cases, an optimized distribution of traffic flows could help to improve the situation from a societal perspective. To counteract the aforementioned developments, transport authorities mainly focus on direct interventions in the transport infrastructure (Abdel-Aty et al., 1995), such as introducing speed limits, environmental zones or variable message signs (Wardman et al., 1997). However, these interventions mainly come into place when the traveler has already chosen to drive within the affected area, instead of guiding drivers to a detour, beforehand.

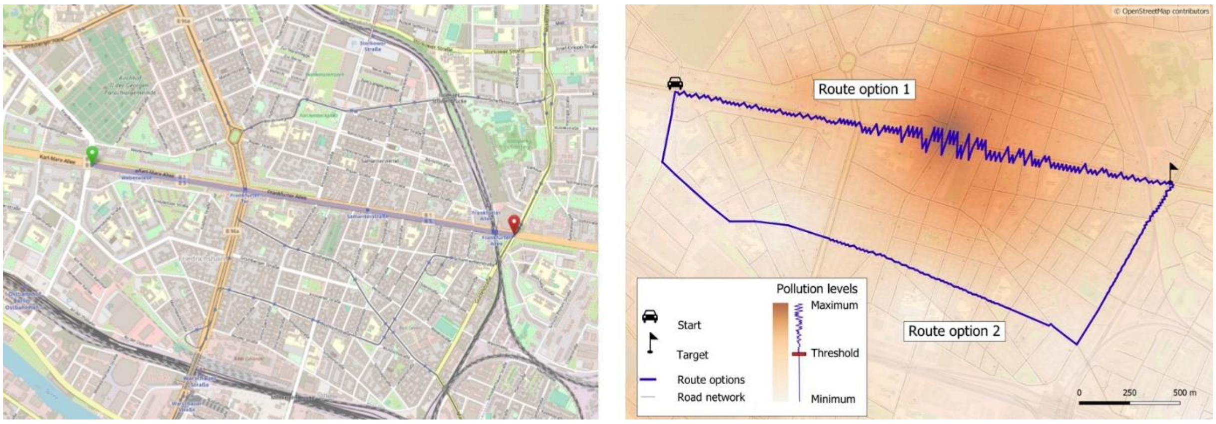
Particularly in unfamiliar environments, most route choice decisions are made based on maps provided by routing applications, before the journey starts. In recent years, mobile navigation devices such as car navigation or phones became increasingly important for route planning, which makes the map as a means of visual communication indispensable. Therefore, clear and intuitive visualization is crucial for conveying the cartographic information. Studies regarding route choice behavior show that drivers tend to make a route choice decision for the individual benefit (Adoko et al., 2013; Ringhand & Vollrath, 2018), whereas drivers are only rarely aware of social aspects for maintaining the efficiency of a traffic system. When planning a trip, people tend to prefer routes that are efficient in terms of travel time, directness, and complexity as main factors (Papinski et al., 2009). But since the individually perceived optimal route differs among travelers, some existing route planning applications do not only take time efficiency into account, but provide personalized route options based on individual preferences for route choice factors (Funke & Storandt, 2015). While an individually preferred route might be attractive to the individual traveler under normal circumstances, various traffic or environmental events or hazards may cause transportation authorities to recommend that an individually preferred route should be avoided. In these cases, it is important to communicate to the traveler to consider choosing a potentially longer alternative route that can help mitigate the hazardous situation.

While the majority of existing services typically provide the most efficient routing options for individual travelers in terms of travel time, newer approaches seek to indirectly guide drivers to a *societally favorable* route that temporarily improves the performance of the entire traffic system. A *societally favorable* route is expected to help improve the traffic or environmental situation in a particular geographic area so that it benefits everyone affected by that situation. An example of this are collaborative routing approaches such as the NUNAV navigation application developed by Graphmasters (2020), which aims to optimize traffic dynamics by reducing traffic jams and thus saving emissions. If the road infrastructure allows, these approaches usually try to assign individual routes to different road users with the same start and destination location, in order to avoid additional congestion due to the same path allocation for all road users (Adacher et al., 2007; Nguyen et al., 2015). Similarly, a recent release of Google Maps intends to nudge travelers to eco-friendly route alternatives by default, instead of suggesting time-efficient routes (Glasgow, 2021). Another approach, introduced by Quercia and collaborators (2014), suggests the shortest path that is also emotionally pleasant.

While the described approaches can contribute to optimizing system-wide traffic, the resulting route recommendations may not necessarily match the individual preferences of the traveler. If the recommended route clearly deviates from the most efficient route in terms of travel time or distance, then the traveler might perceive this route option as less reasonable in terms of individual effort. It is therefore important to communicate the urgency of adjusting the route choice in favor of a *societally favorable* route, in an effective and intuitive way. For this purpose, in this thesis, it is suggested to use cartographic representations to convey the feeling that the traveler might experience when being confronted with the situation. The idea for solving this problem as part of this thesis is to use variations in cartographic symbolization to visually communicate favorable and unfavorable route options to the traveler. Visual communication intends to support the map-readers in their route choice decisions, since on the one hand users might not be aware of which route option is most appropriate to best meet their route choice preferences, while on the other hand they might not be aware of suitable route options that reduce exposure to environmental hazards or that enhance road safety.

Although there are some approaches in research as well as in industry to guide travelers to *societally favorable* routes by means of suitable routing, the visualization of route information is often limited to a simple display of the recommended route options, which are mostly differentiated by colors in form of a route highlight map (Agrawala, 2002), possibly with additional textual information. However, for successfully conveying information on the favorability of route options to the map-reader, maps require a careful and effective design that clearly expresses the map content as well as its message in a cognitively adequate and perceptually salient way (Griffin & Fabrikant, 2012; Otto et al., 2011).

Figure 1.1 shows two different route maps that depict route recommendations between the same start and destination location. However, they clearly differ in the applied route calculation methods, the environmental conditions taken into account, and in the way how the route recommendations are visually communicated to the map-reader. Map (A) shows a route recommendation provided as a result of the *OpenStreetMap* routing service. The calculation is based on the shortest path between the input start (green pin symbol) and destination location (red pin symbol). Since no further traffic, or environmental conditions are taken into account, only one route option is provided as a result, which is the shortest route in terms of distance. The route visualization is limited to a simple overlay of a semi-transparent line of blue color. Map (B) in contrast, illustrates a route map including route recommendations that take environmental conditions such as pollution levels into account for estimating favorability of route options. The visualization further intends to symbolize the level of favorability of route options using line distortion, as well as the area affected by the environmental impact using variations in color, in order to nudge travelers to a more *social route* that avoids the critical area. The cartographic design as applied in map (B) is based on the methodology proposed in this thesis. Please note that all the map data such as background maps and road networks that are included in the figures shown in this thesis originate from the open source project *OpenStreetMap* (2023).



A B

Figure 1.1: Route map visualization provided by a conventional routing service (A) and a visualization suggestion for communicating societally favorable route options using cartographic symbolization for the same pair of start and destination locations (B). Map data from OpenStreetMap.

Like any other type of visual representation, map symbols can evoke different emotional responses in the viewer (Caquard & Griffin, 2018). Therefore, this thesis also investigates how emotions contribute to route choice decision making and the extent to which they play a role in achieving behavior change. Previous research has shown that it is important to appeal to people's emotions (Roeser, 2012) in order for them to understand the moral implications of risks associated with environmental phenomena. Hence, emotions are suggested to be essential for making rational decisions (Lakoff, 2010). The challenge here is to design maps in a way that the symbolization appropriately communicates the emotions that are expected to be associated with the communicated scenario. The creation of intuitive visualizations that evoke expected emotions should make the presented phenomena more tangible for the map reader and thus contribute more effectively to influencing route choice in favor of a recommended and temporarily favorable route.

Current studies indicate that a behavior change is possible among road users to reach a better distribution of the road traffic (McCall et al., 2015), however, people generally seem to be less willing to change their behavior solely for a societal benefit. Research has shown that despite an increase of information and knowledge about environmental impacts, there is still comparatively little (but growing) awareness among the general population about potential hazards of environmental impacts, possibly due to the consequences not being immediately tangible for most people (Evans & Jacobs, 1981). For example, residents in areas with increased air pollution are likely to welcome measures for improving air quality – as long as they do not involve individual effort (Chin et al., 2019). Therefore, it is important to clearly communicate the urgency of preventing a deterioration of the hazard situation.

In view of climate change, it is important that the carbon footprint of drivers is kept as small as possible. In order to make urban mobility more environmentally and socially responsible, research on sustainable mobility aims to introduce measures that either *avoid*, *shift* or *reduce* traffic. While traffic shift can involve choosing a more sustainable mode of transportation, such as using the bicycle instead of the car, *shift* can also refer to guiding traffic away from particular locations or areas. In this respect, the thesis aims to motivate travelers to reconsider their route choice by shifting their decision towards a socially preferable route. The idea for approaching this problem as part of this thesis is to use different types of cartographic symbolization for visually communicating favorable and unfavorable route options to the traveler – with the goal to influence the traveler's route choice towards a more altruistic decision. The methodology developed in this work involves the visual modification of map elements using different visual variables. While some of the proposed visualization methods refer to the application of established visual variables, the usefulness of further experimental visualization techniques including cartographic generalization methods is investigated.

1.2 Research objectives and key hypotheses

The overall objective of this thesis is directed towards investigating the applicability of cartographic symbolization methods for nudging travelers to routes that are temporarily favorable from a societal point of view.

In this thesis, different design variants for route map representation are developed to visually communicate favorable and unfavorable routes using cartographic visualization methods, based on different types of environmental impact. The methodology involves the visual modification of map elements using different visual variables. While some of the proposed visualization methods involve the application of conventional visual variables such as intensity value, size, pattern, color hue, or other graphical symbols, further approaches developed as part of this work use cartographic generalization techniques, including geometric distortions, to symbolize route favorability.

One of the objectives of the thesis is the realization of an automated calculation and subsequent visual communication of route recommendations using cartographic symbolization. The visualizations are directly based on the underlying traffic or environmental information in the corresponding map sections. While road users are expected to widely accept route recommendations that provide an individually beneficial (e.g., fastest or shortest) route, travelers are assumed to be less willing to accept a detour in order to achieve overall societal benefits from a system-optimal perspective (e.g., avoiding excessive pollution at a given location). The challenge here is to design appropriate map representations that successfully nudge the map-reader towards choosing a societally more beneficial route. The route maps are specifically designed for presentation of route options on large screen before starting a trip – as a support for route choice in conventional routing applications. Hence, the proposed visualizations are not adapted to small display sizes.

In addition to the automatic route map visualization procedure, another objective of the thesis is to conduct user studies to test the usability and effectiveness of the representations. This mainly involves investigating the effects of different cartographic representations on route choice behavior as well as the suitability of the representations for the communication of favorable and unfavorable route options.

Accordingly, this thesis involves two main objectives:

1) The first main objective relates to the design of different route map variants for communicating favorability of routes using cartographic symbolization, and their integration into an automatic system. Since the willingness for adapting route choice might differ depending on the environmental phenomenon as a source for route recommendation, the applicability of the developed method to different scenarios is examined as part of this work. The input data for creating such route visualizations is based on traffic or environmental information.

2) The second main objective of the thesis is the conduction of user studies for testing subjective and objective usability of the visualizations. The usability testing focuses on investigating the effectiveness of different cartographic representations for influencing route choice behavior, as well as the suitability of the representations for visually communicating favorability of route options. Finally, an evaluation of successful design variants for symbolizing favorability of route options in different scenarios is performed, while the findings of this work intend to support map-makers or developers of routing services or navigations systems in their design choices.

Furthermore, three key hypotheses are defined, which will be verified in the further course of the thesis:

Hypothesis 1: Visual communication using cartographic symbolization is effective for influencing a traveler's route choice towards a longer, but *societally favorable* route.

Hypothesis 2: Application of cartographic symbolization methods to route map visualizations can be generalized across different environmental phenomena, while the effectiveness of different types of symbolization for influencing route choice and their suitability for communicating the respective phenomenon vary among different scenarios.

Hypothesis 3: Emotional responses to map symbols contribute to a traveler's route choice decision making.

The three key hypotheses are verified as part of three user studies, which are described in chapter 6 of this thesis, as well as in the publications *Fuest et al., 2021 (Hypothesis 1), Fuest et al., 2023a (Hypothesis 2), and Fuest et al., 2023b (Hypotheses 1, 2, 3)*. Within the three user studies, the key hypotheses are further refined to sets of more specific sub-hypotheses, depending on the research questions of the respective user study.

1.3 Structure of the thesis

The remaining part of the dissertation is structured as follows:

Chapter 2 provides the basic knowledge on which the methodology described in this thesis is built. Since the presented work is based on an interdisciplinary approach located at the intersection of cartography and cognitive psychology, the technical knowledge provided in this chapter originates from different disciplines.

The following chapter 3 provides an overview of previous works that are related to the approach presented in this dissertation. By placing the research idea in the context of the state-of-the-art, a research gap is identified that is intended to be filled by the research results of this thesis.

Chapter 4 introduces the overall research framework developed in this thesis, as well as data preprocessing steps that are required for preparing the automatic route visualization procedure.

Subsequently, chapter 5 presents the main methodological contribution of this thesis related to designing *social* route maps. Detailed information is provided regarding the different visualization concepts developed for symbolizing favorability in route maps, including the use of graphical variations on map symbols and cartographic generalization techniques. Furthermore, different potential design variants of route maps are proposed.

In chapter 6, the usability of the proposed design variants is validated by a set of three different user studies. The studies test both subjective and objective usability with a focus on attractiveness, intuitiveness, suitability and effectiveness of the route map visualizations. Objective effectiveness is investigated by testing the influence of the different visualization methods on influencing a traveler's route choice decision making towards a *societally favorable* route.

Chapter 7 presents the architecture and functionalities of a prototype for an interactive web-based application for visualizing route maps based on the proposed methodology. The performance and usability of the application is verified as part of a user survey.

In chapter 8, the findings of the usability testing are discussed with a focus on their agreement with the previously stated key hypotheses. Furthermore, an assessment regarding *successful* design variants for influencing route choice towards a *societally favorable* route, is provided. The chapter concludes with an estimation of the contribution of the dissertation and suggestions for future research.

2 Theoretical background

This chapter provides the theoretical background that is used for developing the methodology presented in this thesis. Since the research conducted in this work is interdisciplinary, the technical background originates from different scientific disciplines, such as cartography, cognitive psychology and statistics.

2.1 Visual communication with maps

Visual communication in general is the practice of using visual elements such as symbols and imagery to transmit ideas or information. Along with verbal communication and non-verbal communication, visual communication is one of the three main types of communication involving humans. Since the used elements could relate to anything visual, there is a large number of different types of visual communication (Barry, 1997), for example using pictures, charts, signs, animations, videos, infographics, but also map representations. One main challenge in visual communication is that the used visual means need to be designed in a way that the message to be conveyed is clear and understandable for the viewer.

Maps are a common means for communicating information with a spatial context. While there is a large variety of different map types, they are usually classified according to what they attempt to depict. In general, maps can be assigned one of two main types of maps: Either a map that describes the actual landscape (referred to as general reference maps or topographic maps), or maps that describe specific features using landscape as a background (referred to as thematic maps). According to the ICSM (Intergovernmental Committee on Surveying and Mapping of Australia and New Zealand (ICSM, 2023)), however, five different types of maps can be distinguished according to their functionality or purpose: 1) *general reference maps* (also referred to as planimetric maps), 2) *topographic maps*, 3) *thematic maps*, 4) *navigation charts*, and 5) *cadastral maps and plans*. In the following, a description is provided for each proposed map category.

1) General reference maps

The main purpose of a *general reference map* (sometimes also called *base map* or *general purpose map*) is to depict the landscape with its natural and man-made features of general interest and help discovering locations on the map. Therefore, maps that fall in this category are typically intended for widespread public use. Hence, they are designed as rather simple and easy to read – even for novices. Examples of this map type are road maps or tourist maps. Different map elements are typically distinguished by using variations in color or other symbols. Additionally, geographical locations such as cities are highlighted, as well as other geographical features like rivers, roads, or mountains.

2) Topographic maps

Similar to general reference maps, *topographic maps* visualize the landscape including physical features in an area. The major difference is that topographic maps additionally show a detailed visualization of terrain elevation. Hence, one main characteristic is the visual representation of points of equal elevation using contour lines. Furthermore, they focus on visualizing information on settlements (e.g. roads, buildings), or land use categories (e.g. water, vegetation). Since the focus is on showing detail information on the topography of an area, topographic maps sometimes include grid lines to provide information about geographic locations depending on the used spatial reference system. The typical scale of this type of maps ranges from 1:10.000 to 1:1.000.000. Topographic maps are typically created by government or mapping agencies, while following strict specifications (standards).

3) Thematic maps

Instead of focusing on mapping the landscape, *thematic maps* visualize information on a particular topic or theme. This could be anything including a spatial dimension such as population densities, weather maps or geological features. Different from the previously explained maps, this type of map provides additional thematic information to the map-reader, while the level of detail included in a thematic map depends on the specific purpose they are made for. In particular, the presentation of the map itself is secondary to the information that is communicated. Hence, rather than providing precise geographic information, thematic maps intend to communicate a specific message to the map-reader. While general reference maps are typically easy to understand by most people, thematic maps may also require specific knowledge related to the mapped topic.

4) Navigation charts

Navigation charts are primarily used as navigation aids for ships or aircraft (marine and air navigation charts), and therefore usually require expert knowledge for successfully making use of them. This type of map usually combines aspects of all previously described other map types. Similar as topographic maps, navigation charts are typically produced by government mapping agencies. Hence, they need to strictly adhere to well defined standards. The charts can also include information which is important to avoiding accidents – such as obstacles in the water like rocks.

5) Cadastral maps and plans

Cadastral maps depict individual properties, and they are usually managed by governmental mapping agencies. Hence, different than other map types such as topographic maps, cadastral maps are typically presented on a large scale ranging from 1:500 to 1:5.000. The mapped information includes an accurate description of the location of a parcel of land and for what purpose the land can be used. The map may also provide information on the location and shape of buildings, including details such as boundary information. Cadastral maps are frequently used in city planning or house surveying. They are one of the oldest forms of mapping, dating back to the ancient Egyptians who are known to have developed cadastral records to establish ownership of land after flooding of the river Nile.

It is important to note that the above described categorization of maps into five different map types is a suggestion made by the ICSM. Indeed, other categorizations including a smaller or larger number of categories are possible. For example, Anderson (2020), proposes a coarser categorization with the three categories *general purpose maps*, *thematic maps*, and *cartometric maps*. Cartometric maps here describe a specialized type of map that is designed for making accurate measurements, covering the above mentioned categories *topographic maps, navigation charts* and *cadastral maps and plans*.

However, since having a very coarse categorization implies that each map category includes a large variety of related map types, a more fine-grained classification might be useful. Moreover, it is possible that some more specific map types have overlapping features between maps (for example having characteristics of both a *general reference map* and a *thematic map*). While in theory, the categorization aims to define map categories that are distinct from each other in terms of their characteristics, in practice, many existing maps do not fit cleanly into one of the categories, making them a hybrid of different map types. In particular, there is a fine line between considering a map as general reference map or already thematic map, in case additional thematic information is added. This, for example, can be the case, if a road map includes information on traffic or specific route recommendations.

The *road map* is a type of map that is frequently used in the context of road traffic, which focuses on visualizing the road network including roads and transportation links rather than physical geographic information. In the general sense, road maps are referred to as *general reference maps* that provide an overview of the characteristics of a road network in a specific area. However, when including further information such as traffic conditions or route recommendations, the purpose of the map changes. The additional thematic information communicated in the map leads to this type of map discussing a specific topic, which is then referred to as a *thematic map.* However, in addition to the road network, road maps often provide information on residential areas and visualize the terrain for providing information on land use. Furthermore, a road map often includes a set of points of interests that help navigating within the mapped area. Road maps typically distinguish between road types of different importance by using variations in symbology (e.g. a thicker line for roads of higher importance). Different road types are usually distinguished by using specific map symbols, which each symbolize the same type of object across different maps. In official map material (e.g. by national mapping agencies), the representation of these symbols is standardized. In case a road map shows a visual representation of traffic flow for the represented road network, this type of map can be referred to as a traffic congestion map.

A special type of a road map is a *route map*, which specifically depicts or highlights one or several routes as a path between different locations in the map, while sometimes providing additional information on travel times or other information that is relevant for the traveler. One of the earliest known route maps that depicts the topological connections between cities at a high level of detail is the *Tabula Peutingeriana*, which illustrates the Roman road network in the late Roman Empire from the British Isles, via the Mediterranean and the Middle East to India and Central Asia (Weber, 1976). The map is an early example of a *strip map* that specifically focuses on depicting one specific route (Agrawala, 2002). While the map includes all relevant information to follow routes between different cities (cities are for examples visualized by symbols with varying size to indicate importance), the geographical information is presented in a highly schematic format, including large distortions in the geometry of the road network and the shape of the land masses. Even earlier examples date back to as early as around 1160 BC, when the Turin Papyrus Map has been created, which illustrates routes through Wadis in ancient Egypt (Harrell & Brown, 1992). While the existence of route maps in early times confirms the importance of this type of map as a supportive medium for travelers to safely reach their destination, in recent times, digital route maps have gained importance, particularly as part of in-car navigation systems. Current navigation systems or routing services that feature a route map representation of the routing information typically recommend the best route option based on a pre-specified factor, while sometimes providing multiple possible route options between which the user can choose. In case time efficient routes are recommended, the presented route alternatives usually do not differ largely from the best option in terms of travel time.

In most cases, route maps show recommended route options as highlighted on a general road map (*route highlight map*) (Agrawala, 2002), for example by using a colored line, which often makes the route visualization difficult to distinguish from the background map. However, since few variations in map symbols are used, the usefulness of conventional route map designs for communicating favorability of route options related to different environmental factors is suggested to be limited. Possible types of symbolization to be applied to route maps for communicating effectiveness of routes are discussed in chapter 5 of this thesis.

2.2 Route choice factors

When moving in an environment, we are inevitably confronted with the task of making a decision of which path to follow – irrespective of the type of the environment. However, relevant factors for route choice largely depend on individual factors such as the choice for a mode of transportation or the trip purpose. This thesis mainly focuses on route choice behavior of drivers, hence route choice factors are reviewed with a focus on car drivers.

Factors that influence a driver’s route choice have been investigated by many researchers. An overview of route choice factors based on user research is for example provided in the work of Papinski and collaborators (2009), in which commuters described their attitudes and preferences for their selected routes for home-to-work routes. Route choice factors can be roughly structured into three main categories: 1) *Individual factors*, 2) *network-related factors*, and 3) *temporary factors*.

Table 2.1 provides an overview of possible factors that are used in the context of drivers' route choice. Please note that the list is not comprehensive, but provides more of an overview of factors frequently researched in literature.

Table 2.1: Overview of different route choice factors.

Individual factors	**Network-related factors**	**Temporary factors**
Trip purpose	Travel time	Safety
Driving experience	Distance	Traffic reliability
Spatial abilities	Route directness	Congestion
Driver's patience	Road type	Unexpected obstacles
Time pressure	Network density	
Flexibility	Number of turns	
Familiarity with area	Traffic light / signs	
	Red light duration	
	Path simplicity	
	Longest leg first	

The first category of route choice factors addresses individual differences, which particularly relates to factors that depend on the driver's personal requirements, behavior and preferences. The choice for a specific route usually depends on the purpose of the trip (Ramaekers et al., 2013). Further factors address the driver's patience, spatial abilities, familiarity with the area, flexibility, time pressure or the driver's experience (Ben-Elia et al., 2008). Based on these individual factors, the driver may have preferences for one or more factors that directly address the characteristics of the route (network-related factors). The majority of researchers (Papinski et al., 2009; Abdel-Aty et al., 1995) agrees that the *time* required to reach the target can be considered as the most relevant factor for choosing a route. In particular, drivers prefer travel time over *distance* measures for making route decisions. Another relevant factor that affects route choice behavior, is the *path simplicity*. Bailenson and collaborators (1998) argue that drivers prefer straight roads as compared to more complex, curved road shapes. Similarly, in case the area to be traversed consists of a *very dense road network*, drivers tend to avoid the most cluttered parts, in order to minimize the chance to accidentally choose a wrong turn. That is, a route, which involves fewer turns is suggested to be easier to follow than a route with a large number of turns. Although considered as a network-related factor in this thesis that characterizes the route, the actual travel time highly depends on other factors including some of the mentioned individual, network-related and possibly also temporary factors.

Another important factor discussed in literature is that drivers prefer to choose routes with a smooth traffic flow, which gives a feeling of continuous movement. Consequently, drivers prefer to avoid routes that pass a lot of traffic lights or stop signs (Papinski et al., 2009). Particularly a high red light duration is not preferred by many travelers. Ringhand and Vollrath (2017) showed that drivers are willing to accept a longer route alternative, in case the waiting time at traffic lights would be minimized.

Importantly, route choice is not to be defined as a fixed decision that is only performed once, before starting the trip. Route choice can rather be classified into a pre-trip decision making process and spontaneous on-route decisions. On-route decisions are predominantly made in case there is a temporary factor affecting the time-efficiency of the pre-selected route. A common case of temporarily influenced route choice behavior is adapting to on-route congestion (Papinski et al., 2009). In case of a traffic-related event such as congestion, which results in the traffic situation to deviate from the usual situation, all these factors affect, if the drivers stick to the previously planned route, or if they deviate from the original route choice. Golledge and Garling (2001) further report that travelers tend to adapt their route choice in case of unexpected obstacles along the route. Further factors suggested to be considered are the likelihood of being patrolled by the police, avoiding unsafe areas, or the exposure to truck traffic. In this context, results from the study conducted by Papinski and collaborators (2009) based on a comparison between planned and observed routes further revealed that about 20 % of travelers deviate from their planned route when making a route choice decision. This indicates that drivers might also be willing to adapt their route choice preferences, in case an initially not preferred route is communicated as effective.

As it has been shown, research regarding route choice factors indicates that in addition to travel time, there are a lot more factors involved that can possibly influence a traveler's route choice behavior. This makes the route choice process highly context-specific and depending on individual differences. In this thesis, some of the described preferences for route characteristics in route choice are used as a basis for developing the symbolization variants for influencing route choice. Given that travel time is reported to be an important factor for route choice, the challenge is also to effectively communicate the favorability of a potentially non-time-efficient route in case of a negative environmental impact on the time efficient route.

2.3 Cartographic symbolization

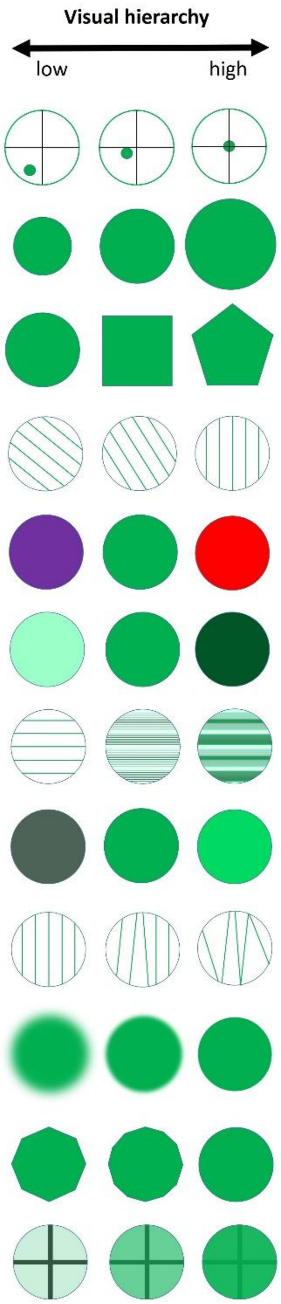
Cartographic symbolization is the problem of appropriately and creatively signifying geographic data by using so-called *visual variables* (DiBiase et al., 1992). In the following, different concepts of cartographic symbolization such as visual variables, cartographic design tools and cartographic generalization techniques are described.

2.3.1 Visual variables

This sub-chapter provides an overview of previous research conducted regarding the definition of visual variables as a cartographic means of visually communicating spatial phenomena. In cartographic visualization, visual variables describe the graphic dimension across which a map or other type of visualization can be varied to encode information (Roth, 2017). The original set of visual variables has been proposed by the French cartographer Jacques Bertin in the 1967 released book *Semiology Graphique* (Bertin, 1967), while the English translation of the book has been released in 1983 (Bertin, 1983). The concept of a visual variable is based on *semiotics,* which is the study of symbols and signs and how they are used for communicating information in different cultures (Jégou, 2019). In the context of cartographic visualization, semiotics can be used to define the way in which a map symbol represents a geographic phenomenon, and how the map user interprets the provided information.

Although the concept of visual variables is considered one of the most influential theoretical frameworks in cartographic design, nowadays there exist various different taxonomies (Roth, 2017). Some of these taxonomies not only include the original visual variables as identified by Bertin, but also consider adapted sets of visual variables as proposed more recently by other researchers.

In this thesis, the description of visual variables focuses on the original visual variable set as proposed by Bertin (1967), as well as on notable and widely accepted additions made by Morrison (1974) and MacEachren (1995).



	Associative	Selective	Nominal	Ordinal (ordered)	Numerical (quantitative)
Location	✓	✓	G	G	G
Size	✗	✓	G	G	G
Shape	✓	✗	G	P	P
Orientation	✓	✓	G	M	M
Color hue	✓	✓	G	M	M
Color value	✗	✓	P	G	M
Texture	✓	✓	G	M	M
Color saturation	n/a	n/a	P	G	M
Arrangement	n/a	n/a	M	P	P
Crispness	n/a	n/a	P	G	P
Resolution	n/a	n/a	P	G	P
Transparency	n/a	n/a	M	G	P

Figure 2.1: The visual variables and their appropriateness for different levels of organization, G = good, M = marginal, P = poor, n/a = information not available. Reproduced from Roth (2017).

Figure 2.1 provides an overview of the twelve different graphical variables that are commonly referred to in literature as *visual variables*. For each visual variable, graphical differences are illustrated along with an indication, if a visual characteristic rather ranks high or low in visual hierarchy. The *visual hierarchy* of importance in this context describes, to which extent the characteristics of a manipulated map symbol *stand out* on the map space. Hence, visual characteristics ranked higher in the visual hierarchy tend to more strongly attract the map viewer's attention than other characteristics of the map symbol and therefore are expected to be more effective for visual communication. Furthermore, each visual variable is estimated as good, marginal, or poor for nominal, ordinal, and numerical levels of measurement (MacEachren, 1995). The *nominal* level of measurement applies, if the data can only be categorized, while *ordinal* data can be categorized and ranked. In case of an *interval* level of measurement, the data can additionally be evenly spaced, while data measured on a *ratio* scale additionally has a true zero point.

The figure also provides information about the applicability of different visual variables according to *levels of organization* (associative, selective, ordered and quantitative perception). In the following, the different levels are explained in detail.

2.3.1.1 Levels of organization of visual variables

The processing of each visual variable by the eye-brain system is predicted by principles of perceptual psychology. Accordingly, the use of one specific visual variable might be more appropriate than other variables for a certain mapping task. Bertin (1967) determined four *levels of organization* of visual variables based on principles of perceptual psychology. Accordingly, perception can be 1) *associative,* 2) *selective,* 3) *ordered*, or 4) *quantitative*. In the following, the different levels of organization are briefly explained.

1) Associative perception

For an associative visual variable, variations in the visual dimension are perceived with equal weight, which allows the eye to perceive all map symbols with the same variation as an associated group. In particular, no variation dominates visual perception, so that the eye is not drawn to one specific variation over other variations. According to Bertin (1967), the visual variables location, shape, orientation, color hue, and texture can be considered as associative. Color value and size, however, can be considered as dissociative visual variable, since in case of color value, the eye is drawn to the darker color values, while in case of size, the eye is focusing on larger sizes.

2) Selective perception

A selective visual variable allows the eye to focus individually on each variation of the visual variable across the visualized scene. Hence, using a selective visual variable, it is relatively easy for the eye to visually isolate a particular category of map symbol across the map. According to Bertin (1967), shape is considered to be the only visual variable that is not selective. Therefore, the visual variable shape is for example useful in qualitative point datasets, when each map symbol should be interpreted individually.

3) Ordered perception

In ordered visual variables, one variation is perceived as *more* or *less* than another variation. This means that the different variations of an ordered variable are perceived as ranked. While for example, a symbol with a darker color value is perceived as *more* as a symbol with a light color value, a specific color hue is usually not perceived as *more* than another hue. According to Bertin (1967) location, size, color value, and texture can be considered ordered visual variables, while according to MacEachren (1995) color saturation, crispness, resolution, and transparency are also strongly ordered visual variables. Texture is described as only being marginally ordered.

4) Quantitative perception

Quantitative perception is an extension of ordered perception. Quantitative visual variables allow estimating numerical values from variations in the variable. According to Bertin (1967), quantitative perception only applies to the variables *location* and *size*. Regarding *size*, for example, it is possible to estimate how much *more* a large symbol is than a smaller symbol. Such an estimation, however, is not possible in a similar way for *color value*. Although ordering is possible, for *color value* it is difficult to estimate how much *more* a dark symbol is than a light symbol.

MacEachren (1995) has estimated the appropriateness of application of a visual variable given the level of measurement of the attribute information, which is also denoted *syntactics*. Accordingly, nominal information is most appropriately encoded by unordered visual variables such as color hue, orientation, and shape, while ordinal information is best represented by visual variables that are ordered, but not quantitative - such as color value, color saturation, crispness, resolution, and transparency. Appropriate visual variables for encoding numerical information are quantitative variables such as location or size. However, these variables can also be applied for nominal and ordinal information due to their visual dominance.

2.3.1.2 ‘Original visual variables’ as proposed by Bertin

In the following, descriptions of the visual characteristics and common application areas of each visual variable are provided. Additionally, it is discussed which visual characteristic of the visual variable is commonly perceived with highest importance in the *visual hierarchy*. Importantly, higher importance in visual hierarchy could relate to the map symbol representing a phenomenon perceived as positive (or a desirable situation), negative (or an undesirable situation), or simply representing a neutral, informative value that has no positive or negative connotation. In fact, the same type of modification in map symbols can relate to communicating different phenomena. For example, a map using variations in line size may communicate a thick line as a large amount of traffic. Another map could use the same type of symbolization for representing a low amount of traffic on roads with large capacity as thick lines.

Bertin (1967) originally described the following set of seven visual variables that can be manipulated for encoding geographic information.

Location

The visual variable *location* describes the position of the map symbol relative to a coordinate frame. While in most cases, *location* is used to represent the spatial component of information in cartographic design, it can also be used for representing attribute information. This is for example achieved in isoline maps, while isolines represent locations of equal attribute values. In 2-D representations, map symbols located close to the center of the map, are ranked higher in visual hierarchy, while in 3-D representations, map symbols perceived as larger or closer to the viewer are ranked higher.

Size

The visual variable *size* describes the amount of space occupied by a map symbol. The size of a map symbol can be varied for point, line and polygon geometries, while in case of a line geometry, size is referred to as the thickness of the line that is varied by different attribute values. Larger map symbols are usually ranked higher in visual hierarchy.

Shape

The visual variable *shape* describes the external form of a map symbol. The possible shape of a map symbol can range from rather abstract, simplistic forms such as squares, circles or triangles, to more complex, iconic forms. Map symbols with a more recognizable, complex shape rank higher in visual hierarchy. The visual variable *shape* is closely related to the concept of a *sign* explained later in chapter 2.3.2.

Orientation

The visual variable *orientation* relates to the rotation or direction of a map symbol compared to the individually defined *normal* orientation. A typical application area of orientation as a visual variable are flow maps for indicating directionality of flow. Individual map symbols that are misaligned to the normal alignment rank higher in visual hierarchy, as well as clusters of map symbols that have the same orientation.

Color hue

The visual variable *color hue* is one of three visual variables that use different dimensions of color – the other two are color value and color saturation (as introduced below). Color hue describes the dominant wavelength of the map symbol on the visible portion of the electromagnetic spectrum (Roth, 2017). Being particularly relevant in the context of thematic mapping, variations in color hue are for example used to encode different categories in choropleth maps. Red colored map symbols are referred to as ranking highest in the visual hierarchy, while blue symbols tend to rank lowest.

Color value

The visual variable *color value* (sometimes also referred to as *lightness*) is described as the relative amount of energy emitted or reflected by the map symbol (Roth, 2017). In other words, color value can be referred to as the amount of black in a map symbol. Color value is particularly applicable for ordinal or numerical information. The perception of visual hierarchy depends on the background color of the map, on top of which the variations in color value are visualized. On maps with a light background, dark map symbols rank highest in visual hierarchy, while on maps with a dark background, light map symbols rank highest.

Texture

The last visual variable of Bertin’s original set of visual variables is *texture* (sometimes also referred to as *pattern*). The variable texture is referred to as the coarseness of the fill pattern within the map symbol. According to Caivano (1990), texture is described as a visual dimension with three different components: the directionality, the size and the density of the texture units. Accordingly, map symbols that are characterized by a denser pattern rank higher in visual hierarchy.

2.3.1.3 Visual variable additions

While the previously described variables relate to Bertin’s original set of variables, over time, several extensions of the list have been proposed by various researchers. Some of the additions are nowadays commonly recognized as valid visual variables. Two additional visual variables have been proposed by Morrison (1974): *Color saturation* and *arrangement*.

Color saturation

Similar to the previously described visual variables color hue and color value, the visual variable *color saturation* is related to the perception of color. Color saturation (sometimes also referred to as *intensity* or *purity*) is described as the spectral peakedness of the map symbol across the visible spectrum (Roth, 2017). More specifically, saturation relates to the amount of grey in a map symbol. Saturated map symbols rank higher in visual hierarchy than de-saturated map symbols.

Arrangement

The visual variable *arrangement* describes the layout of graphical marks constituting a map symbol and ranges from perfectly aligned regular structures to arbitrary placed, irregular structures. Particularly map symbols with an irregular, clustered arrangement rank high in visual hierarchy.

With the emergence of digital cartography, MacEachren (1995) proposed three additional visual variables as an extension as a further extension of Bertin’s visual variable set. The three proposed variables *crispness*, *resolution* and *transparency* became particularly practicable with the large-scale introduction of digital map production methods. Furthermore, they are frequently used for visualizing levels of uncertainty concerning the mapped information (Kinkeldey et al., 2014).

Crispness

The visual variable *crispness* (sometimes also referred to as *fuzziness*) describes the degree of either sharpness or blurriness of the boundary of the map symbol. Crispness is widely used in the context of uncertainty visualization for representing the level of uncertainty of spatial information. Map symbols with a crisp boundary rank high in visual hierarchy, while map symbols with a fuzzy boundary rank low in visual hierarchy.

Resolution

The visual variable *resolution* refers to the spatial precision at which the map symbol is visualized. The idea of mapping variations in resolution of spatial objects originates from the concept of cartographic generalization, which commonly refers to the meaningful adaption of the level of detail and complexity of map objects depending on variations in map scale. The different levels of abstraction are used to encode information. While in a vector-based map visualization, resolution relates to the degree of detail regarding the depiction of line or polygon objects, in a raster map, resolution relates to the coarseness of the grid size. Map symbols with a high level of detail tend to rank highest in visual hierarchy.

Transparency

Transparency is referred to as the amount of blending between a map symbol and background (MacEachren, 1992). The variable is also referred to as *fog*, relating to the visual effect of an opaque barrier impacting the clarity of the underlying map symbols (MacEachren, 1995). Opaque map symbols tend to rank high in visual hierarchy. Due to similar visual characteristics, the visual variable *transparency* can produce a similar visual effect as color-based variables such as *color value*.

2.3.1.4 Experimental visual variables

In addition to the previously described commonly accepted, classic visual variables, researchers have proposed alternative ways of representing variations in attribute values for visually communicating spatial information. An experimental visual variable could also be a variation or adaption of existing visual variables.

An example of an *experimental visual variable* is *scribble* as introduced by Carroll and collaborators (2020). The authors propose a visual variable that creates visual variations using a *scribble* technique for symbolizing visual confusion. Accordingly, paths that have been added a dense overlay consisting of scribbly lines are communicated as less optimal, while lines representing optimal routes are not overlaid by any scribble. In the context of their study, the authors successfully applied this technique to communicate an ‘optimal path’ on a route map.

2.3.1.5 Conjunctions of visual variables

It is further possible to combine two different visual variables for the purpose of attempting to amplify the impact of symbolization of the attribute information. Another purpose could be to represent multiple attributes in a bivariate display (Roth, 2017). In case of a bivariate map, visual variable conjunctions can either be homogeneous (same visual variable used in different ways), or heterogeneous (two attributes are represented by two different visual variables). A homogeneous conjunction manipulates visual variables at the same dimensionality (point, line or polygon), while a heterogeneous conjunction usually applies manipulations at different symbol dimensionalities.

Visual variable conjunctions differ in terms of selective attention, which is the ability to focus on one visual variable while ignoring others. Four conditions of selectivity are distinguished: *separable*, *integral*, *configural*, and *asymmetrical*.

For a *separable conjunction*, the selective attention of both attribute encodings is unrestricted, which means that the distribution of attributes can be seen without one attribute restricting the other. Hence, the user focuses on each attribute scale individually. Separable conjunctions for example occur when using the non-selective visual variable *shape*. Other examples are combining two dissociative visual variables such as *size* and *color value*.

Opposite to separable conjunction, for *integral conjunction*, it is difficult to focus on each attribute individually, but relatively easy to see similarities and differences among the two attributes. Color schemes as recommended for bivariate choropleth maps often use integral conjunction.

For a *configural conjunction*, it is possible to focus on each attribute, but there exists also a visual cue that supports interpretation of the correlation between the attributes. An example for this type of conjunction are homogeneous conjunctions using split symbols.

With *asymmetrical conjunction*, a non-logical emergent dimension causes that one of the two attributes is difficult to be seen. Hence, the map-reader is likely to interpret one attribute over the other. Asymmetrical conjunction is usually applied when one attribute is considered as more important than the other attribute, and tends to occur when using dissociative visual variables such as size or color value together with other visual variables.

Visual variable conjunctions can be useful for effective visual communication, for example when communicating different attribute information in one map. Particularly in terms homogeneous conjunctions, however, map makers need to carefully decide on the visual variables to be used, in order to avoid unnecessary information overload (Bunch & Lloyd, 2006), which might be difficult to process by the eye-brain system.

In this thesis, different types of conjunctions are used primarily for representing the same attribute information, in order to test, if a larger amount of information in symbolization is useful for visual communication.

2.3.1.6 Dynamic visual variables

While the previously described visual variables are suggested to be suitable for application in different forms of 2-dimensional, static map representations, their applicability is limited concerning the symbolization of dynamic phenomena that include a time component. These phenomena could for example relate to traffic dynamics or spatio-temporal environmental phenomena. The simulation of dynamic processes is possible using conventional visual variables, for example by showing a series of map representations to give the viewer the impression of passing time or other changes from map to map within a short period of time. However, these kind of representations may not adequately communicate the dynamic nature of these processes. Therefore, with the emergence of digital cartography and the development of new visualization techniques such as animation, various researchers (DiBiase et al., 1992; MacEachren & Taylor, 2013) proposed a set of *dynamic visual variables* that better address the characteristics of spatio-temporal data. Dynamic variables are visual variables used in individual frames of an animation to encode attribute information and control the temporal characteristics of data visualization. According to DiBiase and collaborators (1992), a combination of dynamic and conventional, static visual variables could help emphasize attributes or the relationship between attributes of the symbolized cartographic objects. Such combinations have for example been applied to traffic accident animation, where symbol duration was combined with symbol size for indicating severity of accidents at an intersection (Moellering, 1976). Slocum and collaborators (1990) further investigated the potential of sequential presentation of choropleth map categories, involving the generation of several scenes from a single static map, with each scene depicting one category of attribute information. The scenes can then be ordered from lowest to highest category, or vice versa.

The six *dynamic visual variables* proposed by DiBiase and collaborators (1992) and MacEachren and Taylor (2013) are: 1) *duration*, 2) *moment*, 3) f*requency*, 4) *rate of change*, 5) *order*, and 6) *synchronization*. In the following, the different variables are briefly explained:

Duration is a function of time, which refers to the number of units of time that an element is displayed in an animation (DiBiase et al., 1992). Hence, duration can be used to control how long a scene will be shown. In this regard, scene duration can be set depending on attribute values of ordinal or interval scaled attribute data. Accordingly, high (or more relevant) attribute values could be emphasized by representing them with longer scenes.

Moment describes the actual moment that an element in the map changes during a cartographic animation.

The *rate of change* is used in describing the change magnitude of an element during animation, relative to the duration of the scene. It represents the magnitude of change per display unit time. Combining the rate of change with other static variables, for example color hue, allows to draw the user's attention to objects of interests based on the attribute data value. Rate of change is a powerful tool to manipulate viewer's perception and therefore should be used with care.

Frequency uses the rate of re-occurrence at which graphical elements appear or change in an animation (Köbben & Yaman, 1995). This can be visualized for example by varying the 'blinking frequency' of map symbols to indicate importance of the visualized object.

The dynamic variable *order* involves presenting individual frames in a given order. This means that spatial variations over time are chronologically shown within different frames. An example for this kind of representation is visualizing changes in the geopolitical status of countries over a longer period of time.

Synchronization describes the relation between two or more phenomena by showing their development synchronously within one animation, and only works for temporal relationships.

DiBiase and collaborators (1992) distinguish three categories of dynamic maps: 1) Maps that emphasize the existence of a phenomenon at a particular location (for example a point symbol that flashes on and off to depict the locations of natural disasters), 2) maps that emphasize an attribute of the phenomenon, and 3) maps that represent change in a phenomenon's position or attributes.

In case of a flashing of a map symbol, the dynamic visual variable duration attempts to reinforce the static visual variable for visualizing attribute information. This flashing intends to help focusing attention on the corresponding patterns visualized by means of static variables. While in the first two categories, dynamic variables are used for enhancing static representations, the third category *visualizing change* uses dynamic variables for visualizing phenomena that change through time and space. The visualization of change can be distinguished into three types: *Spatial change* ('fly-by', sequence of views of static surface, in which the viewpoint of the observer changes gradually), *chronological change* (time-series sequences), and *attribute change* (change of object position in attribute space).

According to the previously described levels of organization of static visual variables, research has been conducted towards proposing a similar classification for dynamic visual variables. As shown in Table 2.2, a user survey conducted by Köbben and Yaman (1995) revealed that the dynamic visual variable *moment* seems to be less useful for usage in cartographic animations. Reactions regarding *duration* and *rate of change*, however, were mostly positive. Animations using *duration* or *rate of change* primarily conveyed a strong sense of order and to some extent a sense of quantity. The variables *frequency* and *order* were evaluated as fairly effective and conveyed a fair sense of *association* and *order*.

The results give an indication about which dynamic variable to use for which level of organization, however it should also be noted that representativeness of the results might be limited, due to a small sample size. The findings further indicate that selection, which is important for visual communication, does not seem to be effectively addressed solely by using dynamic visual variables. Therefore, for effectively communicating dynamic geographic phenomena, it seems that a combination of static and dynamic visual variables may provide the most useful results.

Table 2.2: Perceptual properties of dynamic visual variables (adapted from Köbben and Yaman (1995)).

Dynamic variable	Perceptual property			
	Association	*Order*	*Quantity*	*Selection*
Moment	weak	-	-	-
Duration	-	strong	fair	-
Frequency	fair	fair	-	weak
Order	fair	fair	-	weak
Rate of change	-	strong	weak	-
Synchronization	*not tested*			

Although from a visual point of view, sequenced, animated maps are often preferred over static map representations by map users, Slocum and collaborators (1990) found that their effectiveness in terms of recalling patterns did not outperform effectiveness of static maps. This indicates that map-makers need to carefully consider, if a dynamic representation is beneficial for communicating attribute information, or if a static representation is more appropriate.

While not being in the focus of this thesis, the influence of dynamic visual variables compared to static visual variables is explored in a follow-up user study described in chapter 6.2.11.

2.3.2 Cartographic design tools

In cartographic design, a large number of different design tools are distinguished. The basic elements of cartographic design are *point*, *line* and *area*, as well as the composite signs *cartographic symbols*, *diagrams*, *half tone* (e.g. shading) and *map font* (Hake et al., 2002).

The application of the graphical element *point* is not considered in the scope of this thesis, since the environmental scenarios to be addressed rather relate to either linear or areal phenomena.

In cartographic visualization, *lines* are either used for representing linear objects such as paths, roads, or rivers, or object boundaries such as properties, forests or lakes. Graphical variations for to the graphical element *line* primarily relate to line size, line color or line pattern. Further options include lines composed of symbols, or font added to the line. Moreover, isolines are widely used for representing points on the map with the same value.

Areas mostly represent geographic objects such as city districts or natural features such as lakes. Areas are usually delimited by a visual boundary that symbolizes the delimitation to other objects. For simple areas, graphical variations are mostly applied as variations in color hue or value.

In addition to graphical variations applied to the basic graphical elements point, line and area, *cartographic symbols* can be used to show object characteristics by applying graphical variations. Cartographic symbols can either take abstract, geometrical forms such as circles, triangles or rectangles, or more specific, figurative forms. An overview with examples of different forms and arrangements of symbols is provided in Figure 2.2.

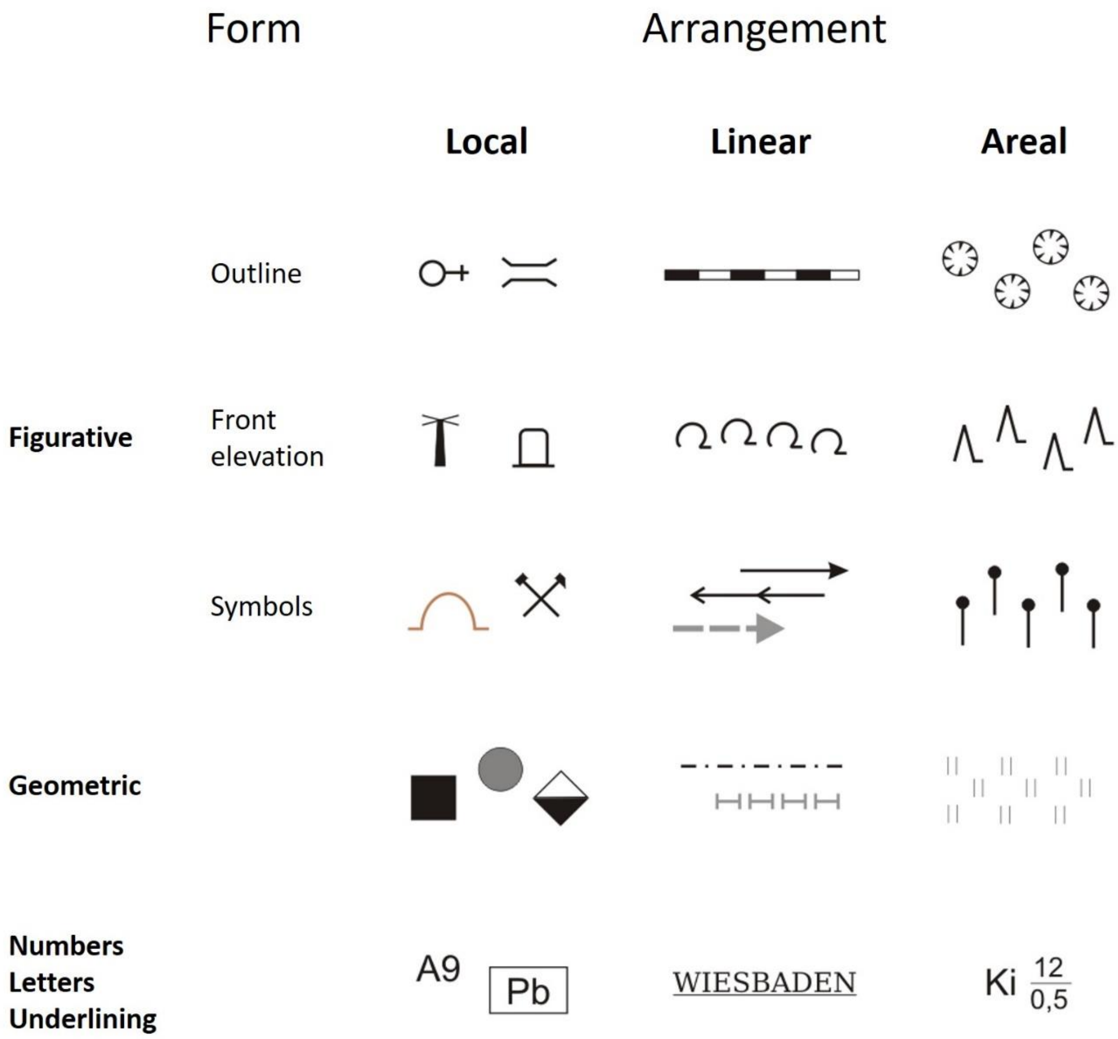


Figure 2.2: Examples of forms and arrangements of cartographic symbols. Adapted from Hake & Grünreich (1994).

Figurative symbols can be outlines or front elevations of objects in schematic or realistic representation, but also symbolic representations using generally understandable, abstracted renderings of objects. Geometric symbols range from simple forms such as circles, triangles or squares, to dashed- or dotted lines and hatchings. Finally, numbers and letters are primarily used in contexts where they are easier to understand than conventional symbols, while underlining provides additional qualitative information.

While a local arrangement of symbols relates to the representation of the location of individual symbols, a linear arrangement of symbols mostly involves showing a sequence of geometric or figurative symbols. This sequence of symbols can be either linked with lines, or visually disconnected. Additionally, it is possible to link a sequence of linear symbols with font. An areal arrangement of symbols can involve showing a symbol repeatedly distributed over an area. Such areas can be either delimited by a line, or simply by the end of the occurrence of the symbols.

In cartographic visualization, *diagrams* are graphical means for visualizing primarily quantitative data, such as statistical values. *Map font* has a relatively low geometric expressiveness, but it is an important explanatory element of the map. Furthermore, qualitative information can be visualized by varying shape and color, while quantitative information can be visualized by varying font size.

The described cartographic design tools can be combined with the visual variables (chapter 2.3.1) to form a large variety of different cartographic design variants for representing graphical differences of map objects.

Sign as a further concept

The concept of a sign is strongly related to the previously described figurative forms of cartographic symbols as part of the cartographic design tools, while making a further distinction based on the semantic aspects of a symbol.

A sign always has a *signal aspect* (a physical pattern) and a *meaning* (sematic content implied by the sign). It can take many different forms, including visual forms such as road signs, photographs, or paintings, but also forms such as letters, numbers, or non-visual forms such as sounds. According to the semiotic theory, Peirce (1991) categorized visual signs for denoting an object into three different types: *icon*, *index* and *symbol*.

An *icon* has a physical resemblance to the object being represented. Hence, the meaning of an icon can be directly inferred by seeing the visual representation. Examples of icons are a picture of a person or a realistic illustration of an object. Defining a sign as an icon highly depends on how *physical resemblance* is interpreted.

An *index* implies a connection between the sign and the object to be signified. Understanding the meaning of an index therefore requires to guess the relationship between sign and object. An example for an index is the representation of smoke for indicating fire.

The meaning of a *symbol* for denoting an object is learned by law, or based on cultural conventions or social rules that are connected with the object. Hence, understanding a symbol requires to learn its meaning; otherwise, it might be useless to the viewer. An example of a symbol are words from a specific language, whose meaning is culturally learned by the people who speak this language. Other examples of symbols are pictograms such as signs for gender, or logos of a specific, well-known brand. Most of the graphical representations using conventional visual variables can be considered as symbols, since their correct encoding is typically the result of a learning process.

Figure 2.3 shows each one example of an *icon* (a), *index* (b) and *symbol* (c) in the context of representing a power plant and the potential danger associated with it. The illustration shown in (a) depicts the outline of a power plant. Even though the graphic shows a schematic, rather than a photorealistic view of the depicted object, it is clear to the viewer what is shown. Hence, the representation can be described as an *icon* for depicting the object ‘power plant’. The figure shown in (b) features a schematic, black cloud, which intends to represent danger due to emissions caused by industry. To enhance clarity of the symbolization, the text ‘CO_2’ is added within the cloud, which indicates that the visualization should particularly represent CO_2 emissions. Therefore, the sign can be considered as an *index* for representing emissions produced by a power plant. Due to the inclusion of the text ‘CO_2’ the representation could also be considered as a combination of an *index* and a *symbol*. The illustration presented in (c) shows a sign that warns of a biohazard, potentially indicating a location of increased danger. Understanding this *symbol* requires that the viewer has learned about its meaning.

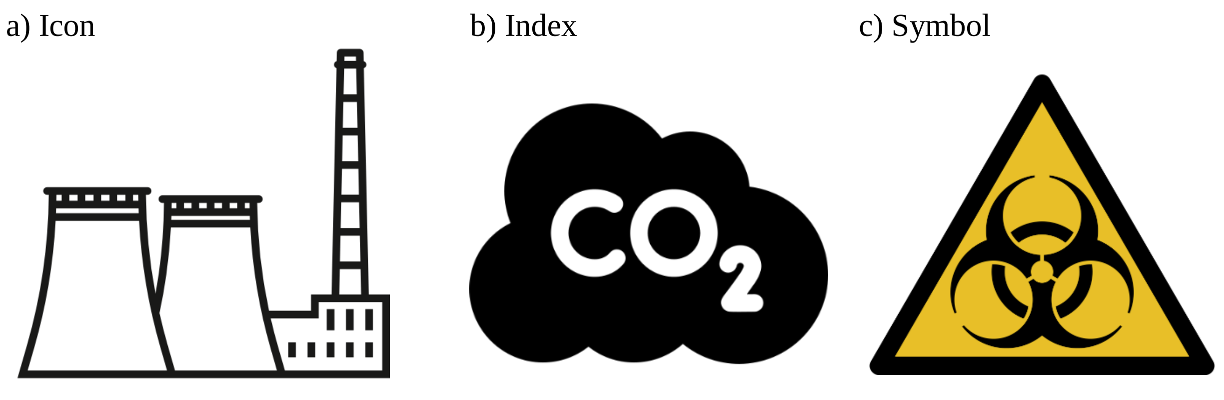


Figure 2.3: Examples of different signs for symbolizing a power plant and the dangers posed by its emissions or a bio-hazard.

While the presented terminology tries to classify signs in terms of how the communicated object functions in signification, in reality, many types of signs show a combination of *icon*, *index* or *symbol* characteristics. Also, the same representation can have different dimensions of a sign. A clock representation, for example, could serve as an icon for depicting an actual clock object, or as an index for symbolizing time.

In this thesis, various different signs are used as part of design variants for symbolizing favorability of route options. In this context, signs are combined with visual variables, such as *size* or *transparency*.

2.3.3 Visual metaphor

One main purpose of cartographic symbolization is to use map symbols in a way that map users would intuitively understand the meaning of the used symbolization. This is highly related to the concept of a *visual metaphor*.

A visual metaphor (sometimes also referred to as *pictorial metaphor*) is the representation of an object by means of visual imagery, while suggesting a particular association or similarity (Carroll, 1994). For some visual metaphors, the connection between the visual image and what they are compared to is based on conceptual similarity, while in some cases it is physical similarity. While the interpretation of a visual metaphor is expected to be similar among different individuals, each person can still understand them a bit differently. An example of a visual metaphor in the context of a route map could be a red-colored road for indicating traffic jam, or a dark cloud layer for indicating environmental hazards such as air pollution.

While the concept of a visual metaphor is important for the purpose of cartographic symbolization, other important application areas that rely heavily on visual metaphors are advertising, for example in print media, or in movie making. Hence, due to their distinct visual message, visual metaphors are often used to persuade or manipulate the perception of the viewer towards a specific point of view.

A special case of a map type that makes extensive use of visual metaphors for manipulating the map-readers perception is a *persuasive map*. Different from conventional scientific geo-visualization, this type of map does not primarily intend to *inform* the user, but use the power of visual communication to *persuade* the map-reader to accept a certain interpretation of the visualized information, in order to promote a particular point of view (Tyner, 1982; Muehlenhaus, 2012). Common characteristics of a persuasive map are strong use of colors, clear contrasts between map objects, the use of emotive symbols or adding a manipulative, and sometimes even aggressive textual description.

Importantly, the visual communication applied to route maps as part of this thesis does not aim to persuade the user, but, according to the concept of nudging (explained in chapter 2.4), rather intends to reinforce an informed decision of the user.

2.3.4 Cartographic generalization and map abstraction

The process of cartographic generalization involves meaningfully abstracting map objects that represent real world objects to a cartographic representation that is useful for a given map scale and purpose (Müller & Wang, 1992). This sub-chapter describes different cartographic generalization techniques that can be applied to route maps either for the purpose of enhancing map readability or for influencing the viewer’s perception. In a first step, it is described, how concepts from cognitive psychology such as map schematizations that are generated in a human’s mind can be useful for creating effective route map representations using different types of generalization techniques. In a second step, the different specific generalization operators are defined and explanations for two different algorithms for automatic generalization (polyline simplification and displacement) are provided exemplarily (Mackaness et al., 2011).

2.3.4.1 Insights from cognitive mapping research

Schematic drawings of route maps are among the most common forms of communicating cartographic information (Avelar & Hurni, 2006). Research in cognitive psychology suggests that people mentally abstract the geographic space when they communicate routes to others, using distortions, simplifications and other generalization techniques, while focusing on the most relevant information necessary for navigation (Agrawala & Stolte, 2001; Downs & Stea, 1973). The knowledge gained about the environment is stored in a *cognitive map*, which is referred to as a simplified, mental representation of a real-world geographic space. The concept of a cognitive map was originally introduced by Edward Tolman (1948). For assessing the level of spatial knowledge and spatial thinking of a person, a commonly applied method is to analyze the spatial configuration of hand-drawn *sketch maps*, which are externalizations of the information stored in the human cognitive map. Sketch maps are usually provided in an abstract, schematized format, and therefore serve as an important means for communicating spatial knowledge about a specific area (MacEachren, 2004; Lynch, 1960). They provide helpful information to learn, which elements and characteristics of the environment (and the route in particular) are necessary to be emphasized; and accordingly which elements can be de-emphasized without a loss of effectiveness for route planning or navigation.

Due to individually different experiences and knowledge about the environment, each person perceives and mentally structures the environment in different ways. Therefore, mental representations of different persons regarding the same environment never exactly match. However, when analyzing sketch maps regarding the elements included, researchers found that there are some recurring patterns, which are observable in most representations (Agrawala & Stolte, 2001; Billinghurst & Weghorst, 1995, Appleyard, 1970, Krukar et al., 2018). Tversky and Lee (1999) report that instead of drawing the route using its original shape, people widely schematize elements like intersections or paths. Intersections, for instance, do not need to be drawn at their exact angle in order to sufficiently travel along a route. Similarly, slightly curving paths are usually not drawn using their exact shape, but a simplified representation that approximates a straight line. Distinct curves along the route, however, are frequently emphasized, since they may serve as an important structural landmark when following the route. In addition to simplifying and distorting the structure of the route and the map elements, people use extra information like cardinal directions, arrows and additional landmark information. Landmarks are particularly used in close proximity to start and end point as well as turning points of the route. Tversky and Lee (1999) further investigated that routes are usually segmented around action points (typically turns), which are depicted in more detail as compared to the remaining route information.

Despite its geometric incorrectness, such a schematized map representation might still be an intuitive and efficient way of representing the environment. That is, because during route following, the traveler does not need to make active decisions, and therefore does not need to be familiar with the exact shape of the road (Agrawala & Stolte, 2001). Researchers further investigated that preserving distances of route segments does not seem to be important information for conveying routes (Tversky & Lee, 1999). Here, it is rather assumed that, in a mental representation, longer distances are cognitively compressed relative to shorter distances depending on the information load they are associated with (Magel & Sadalla, 1980). Golledge and Zannaras (1973) further propose that there is a direct relationship between the cognized distance and the time required to traverse any given path. That is, the travel time based on the given traffic flow on a route is assumed to have an influence on the cognitive perception of the traveled distance (MacEachren, 1980; Saedi & Khademi, 2019). Magel and Sadalla (1980) further addressed the influence of the number of turns in a path on the perception of route length. In particular, they found that routes with a larger number of right angle turns are perceived as longer than routes which included fewer turns.

Figure 2.4 presents an example of a metric map including a route (map on the left, route from waypoint 1 to 6), and a corresponding sketch map example that visualizes the same route (Li et al., 2014). It becomes apparent that the example sketch map includes several of the previously described schematizations, like simplification to straight lines, road length distortion and focusing on relevant geographic information.

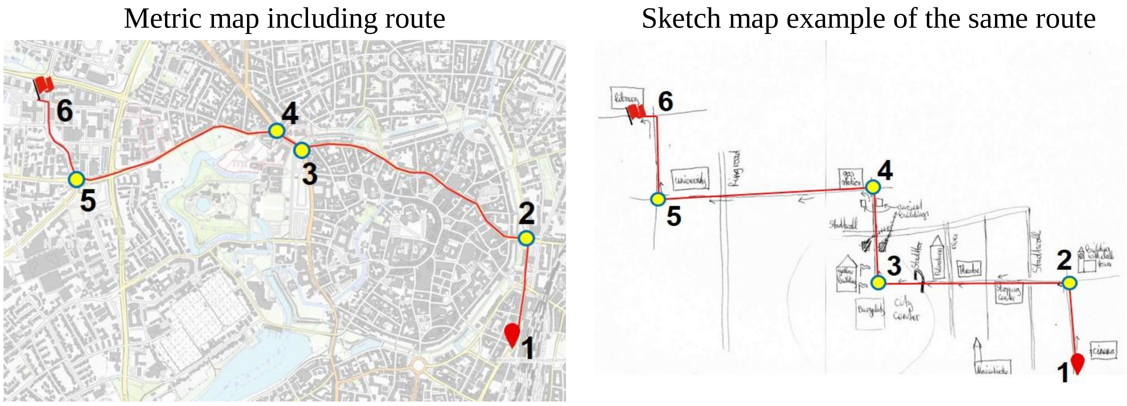


Figure 2.4: Example of a metric route map and a corresponding sketch maps of the same route (Li et al., 2014).

Besides their use in cognitive mapping research, schematic map representations are part of our everyday life. For instance, a schematized *metro map* uses various types of simplifications and only communicates information that is important for the user (Agrawala et al., 2011). Simplifications include the use of schematization (straight lines), adapting distances, and the use of different colors to distinguish lines. Another example of a schematic map is a *destination map*. This type of map often uses two different scales in one map: A small scale to provide an overview of the area, including the city area and major highways, and a large scale map (sometimes added to the map as a stylized magnifier) to provide detailed information focusing on the direct surroundings of the destination, as well as on multimodal information for reaching the destination. In addition to the previously mentioned maps, Avelar and Hurni (2006) further distinguish two types of schematic transport maps: *thermometer diagrams* and *spider maps.* While thermometer diagrams depict a route as a straight or stylized line because it is not relevant to show details of the line path, spider maps represent the most relevant information geographically correct in the middle, and details on the branching lines in a schematic format. Interestingly, depending on the map purpose, a schematic map is sometimes easier to use than a metric map. In case of a schematic map, conveying the topology of the visualized network or spatial structure is more important than providing correct geometric information of the environment.

Due to their purpose of facilitating the map-reader to quickly process the visualized information, schematic transport maps are specifically designed for reducing the *cognitive load* of the map-reader. According to the cognitive load theory (Bunch & Lloyd, 2006), humans have a limited working memory, which can only process a limited amount of information at the same time. Since therefore cartographic representations need to take into account the working memory capacity of map users, schematizations are suggested to be useful for reducing visual complexity in maps.

The described characteristics of sketch maps are closely related to cartographic generalization techniques, as commonly applied in various mapping tasks. In order to improve the overall route map usability for effectively communicating a specific route, Agrawala and Stolte (2001) used a set of generalization techniques. Their idea was to generate route maps based on generalization techniques frequently applied in sketch maps, while suggesting that these types of maps clearly visualize the essential information which is relevant for navigation and omit irrelevant information. Thus, communicating the information included in sketch maps is suggested to be effective for route choice and navigation purposes. In this thesis, some of the applied cartographic symbolization techniques are based on different concepts from cognitive psychology research. This involves the road network to be presented in a way, how it might be perceived while traveling along the route – by using abstractions commonly applied in sketch maps.

2.3.4.2 Elementary processes of cartographic generalization

With increasing use of GIS applications and digital cartography, the problem of map generalization has increasingly become important due to automatic map production on the web. Cartographic generalization is commonly applied in case the mapping purpose requires the visual representation being more effective when using a simpler design. Hence, this technique primarily intends to reduce the visual detail of data when varying the map scale (Sester, 2020). Since it is not possible to perfectly map every detail of a real environment, every map to some extent applies some cartographic generalization. One of the main advantages of applying cartographic generalization and therefore reducing geometric detail is a lower storage space and processing runtime for large datasets.

As cartographic generalization in most cases involves a modification of data representing real world objects, the cartographer must carefully decide on which objects to modify and to which extent, in order to make sure that the map-reader is not experiencing disadvantages from the applied modifications. In the original sense, cartographic generalization methods serve to adapt the amount of information shown on a map to the map scale in order to avoid visual overload and to improve readability of the map. However, on the other hand, the cartographer may also intentionally modify or remove an entire object or details of an object, in order to direct the focus on some specific features in the map space that are suggested to be more relevant than others based on the map purpose (*visual communication*). This way, the cartographer can use cartographic generalization when intending to emphasize specific geographic phenomena and processes, while deemphasizing others (Roth et al., 2011).

Over time, a large variety of cartographic generalization techniques have been developed by researchers. While there are multiple further techniques, Hake and collaborators (2002) propose a set of seven *elementary processes* of cartographic generalization that are widely used in map making. These involve the processes *selection, simplification, aggregation, typification, exaggeration, enlargement* and *displacement*. While the processes *simplification, enlargement* and *displacement* describe purely geometrical operations, the remaining processes can be described as factual with a geometric effect. Figure 2.5 provides for each of the *elementary processes* a visual example of a typical representation in the original map, as compared to a corresponding representation in the generalized map. In the following, a short description is provided for each process.

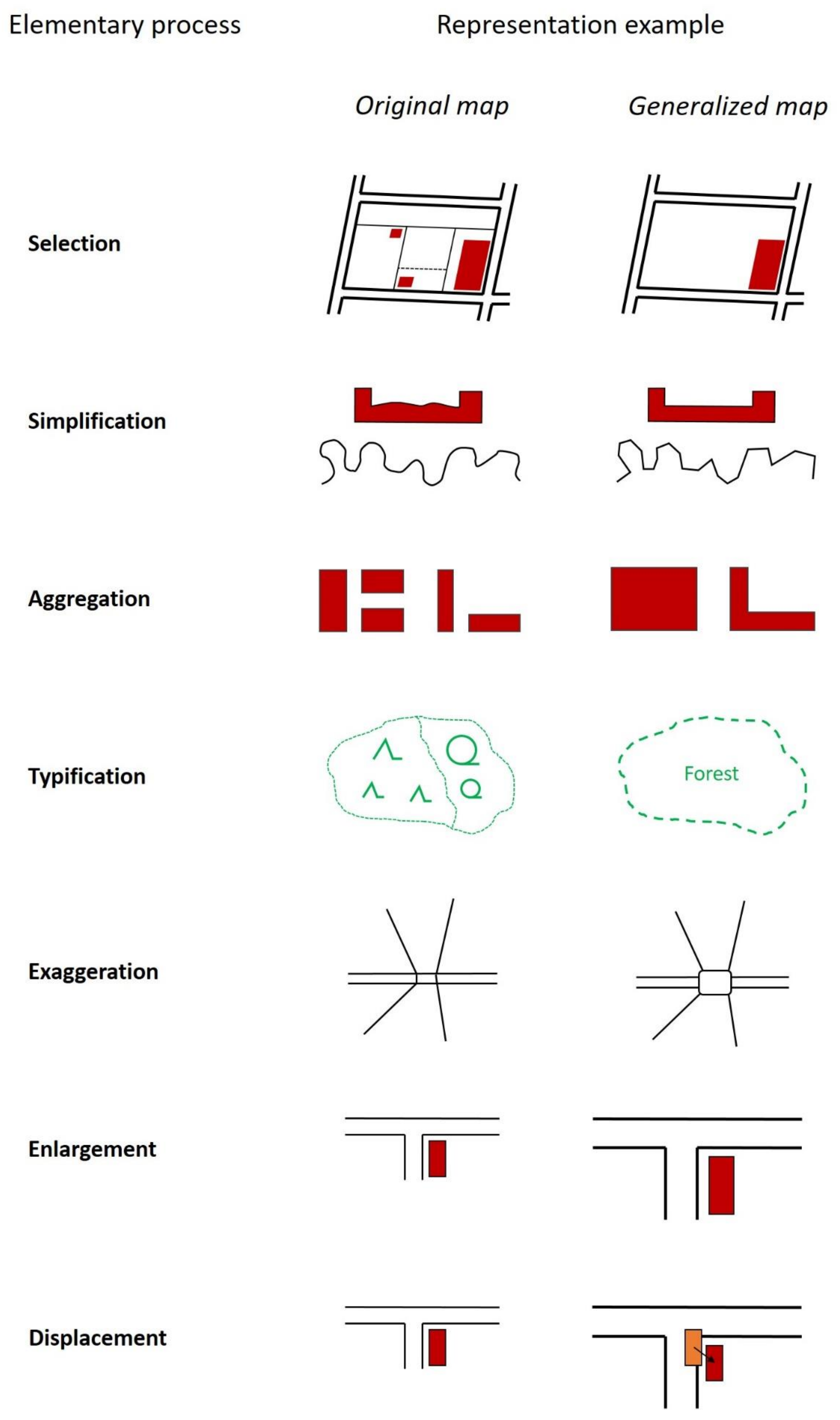


Figure 2.5: Elementary processes of cartographic generalization. Adapted from Hake et al. (2002).

Selection

The process *selection* involves the decision, if a certain object will be displayed or not. In case the map scale causes some objects to become illegible, or if objects no longer fulfill their intended purpose, this process can be used to remove map objects. The process could for example be applied, if a road network features unnecessary detail at a certain map scale, or if features considered as less important should be removed in order to direct the map-reader's focus to the remaining map objects – which then visually 'stand out'.

Simplification

The process *simplification* involves a purely geometric change of an object's shape. This includes, for example, outline simplification of a polygon and polyline simplification, by reducing the number of points that constitute an object. While the simplification process involves an adaption of the map object's original geometry, the overall shape is preserved, in case the applied simplification is not too extreme. For automating the process, various algorithms have been developed to address the problem of line simplification, such as the widely used Douglas-Peucker algorithm (explained in more detail in chapter 2.3.4.3).

Aggregation

The process *aggregation* combines multiple, spatially close objects of the same type graphically by replacing them with a representative object.

Typification

The process *typification* replaces a larger set of objects with a smaller one, resulting in a sparser arrangement of symbols. This procedure is sometimes necessary, if in case of a change to a smaller scale, symbols would overlap, and a sparser representation using a few representative symbols is considered more appropriate. For example, different classes of forests can be combined to form the class forest. This process is accompanied by a loss of information.

Exaggeration

The process *exaggeration* refers to the deliberate exaggeration in the design of forms. Particularly typical object shapes can be given extra emphasis through stroke width or symbol size. While focusing on emphasizing characteristic features of objects, topological relations may not always be preserved.

Enlargement

The process *enlargement* is a purely geometric enlargement of the original objects, typically applied to ensure better visibility of particular objects in the map space. This includes points, line widths, areas and symbols.

Displacement

The process *displacement* is a direct consequence of the enlarged or widened object representation. When changing the map scale without adapting the size of all map objects, spatial conflicts might occur, which should be solved by retaining topological relations between objects. To address this problem, the process *displacement* shifts the position of a map object away from another object to avoid spatial overlap. In order to maintain the relative position of the objects to each other, the objects are displaced at the expense of their positional accuracy. Further research regarding the displacement of map objects has been conducted by Sester (2006). In this context, the program PUSH has been developed, which solves spatial conflicts in arbitrary scaled maps. The capabilities of this program and its application to modifying line objects by enlarging them are explained in chapter 2.3.4.3 of this thesis.

For the described processes, GIS software such as *ArcGIS* or *QGIS* provide built-in tools to facilitate map makers to apply these types of cartographic generalization for optimizing the visual representation of the resulting map.

2.3.4.3 Cartographic generalization algorithms

In this sub-chapter, each one example of a commonly applied cartographic generalization algorithm is provided for the processes (polyline) *simplification* and *displacement*. As described later in this thesis, these algorithms are further used for developing some of the generalization-based design variants.

Douglas-Peucker-Algorithm for polyline simplification

For simplifying polyline objects, several widely used cartographic generalization algorithms have been developed. Examples of such algorithms are the Visvalingam-Whyatt algorithm (Visvalingam & Whyatt, 1993), the Li-Openshaw algorithm (Li & Openshaw, 1992) and the Reumann-Witkam algorithm (Reumann, 1974). In the following, one of the most commonly applied generalization algorithms, the Douglas-Peucker algorithm, is described in more detail.

The Douglas-Peucker algorithm is one of the most commonly applied procedures for performing geometric simplification of line objects. The algorithm is also known as the Ramer-Douglas-Peucker algorithm, named after the developers of the original version of the algorithm, Urs Ramer (Ramer, 1972), David Douglas and Thomas Peucker (Douglas & Peucker, 1973). While there are other uses for this algorithm, such as modifying vector graphics, it is most frequently used in cartographic generalization. The input data for the algorithm is a curve composed of line segments (*polyline*), while the intention is to simplify the shape of the polyline by reducing the number of points. The algorithm further requires the definition of a tolerance value (distance threshold) ε as input, with $\varepsilon > 0$.

Figure 2.6 shows how the Douglas-Peucker algorithm in its original version simplifies the shape of a given polyline using a pre-specified ε value. The algorithm recursively divides the polyline for piecewise simplification. The input is a polyline consisting of a set of points connected by straight line segments (a).

In a first step, the end points of the polyline are automatically marked to be kept and the ε value is specified. Next, the algorithm searches for the point on the curve that is furthest away from an approximating straight line (red line in the figure) that connects the first and last point of the polyline (b). If the point is closer to the approximating line segment than ε (red colored points in the figure), then all points that are not marked to be kept can be discarded. Consequently, the individual line segments are then replaced by the approximating straight line and the algorithm stops.

In case the point furthest away from the approximating straight line segment between the end points of the polyline is greater than or equal to ε (green colored points in the figure), then the point is marked as kept. The algorithm then recursively calls itself for the currently considered part of the polyline, with first defining the approximating line between the first point and the furthest point, and then between the furthest point and the last point (c-f). After the recursion is completed (no more points found to be kept), a new curve is generated as output, consisting only of those points that have been marked as kept (g).

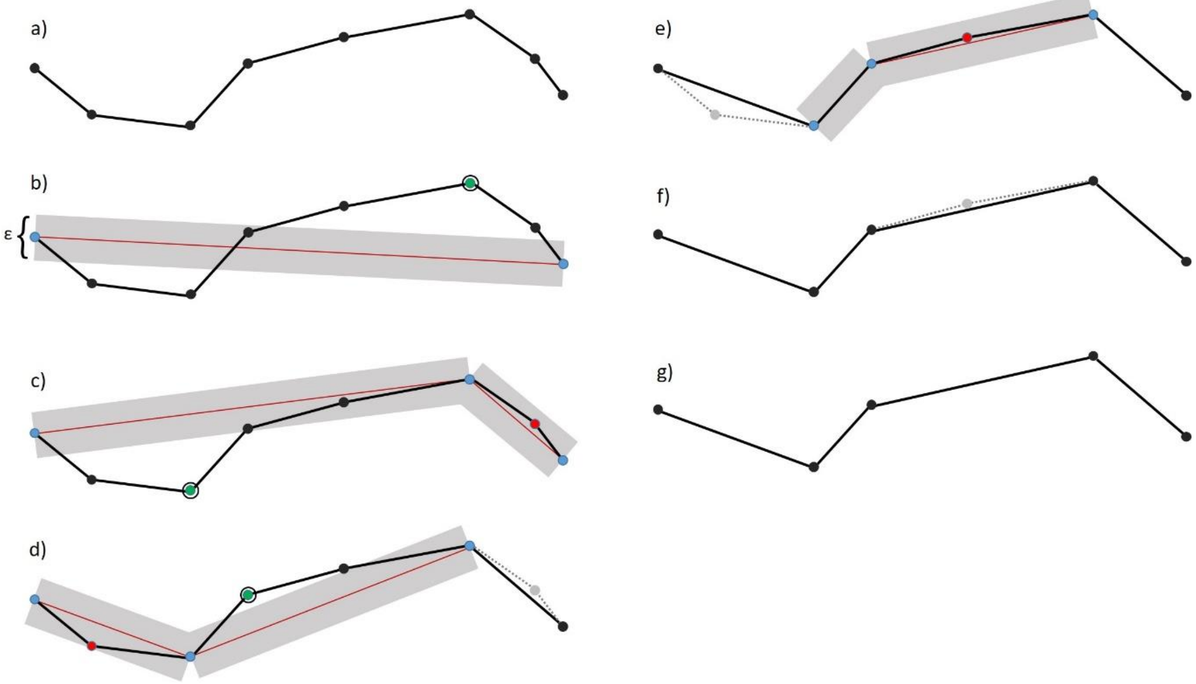


Figure 2.6: Simplification of a polyline using the Douglas-Peucker algorithm.

The choice of the ε value as a parameter is usually made by the user and has a direct influence on the degree of simplification of the polyline. While a very small ε value may result in a polyline that still has a structure very similar to the original line, a very high ε value could result in a strong simplification of the input polyline, in the extreme case simplified to one straight line. While a certain degree of simplification (in the sense of schematization) is expected to be useful for enhancing effectiveness of some representations, very strong application of polyline generalization can make the cognition of conspicuous structures that constitute the original object, more difficult.

Figure 2.7 presents different levels of simplification of the outline of the German Federal State of Schleswig-Holstein using the same map scale. The original state outline is very complex due to two different coastlines (North Sea and Baltic Sea). The most appropriate visual representation depends on the map purpose and the information that the maps intends to convey. While map A presents original data from Bundesamt für Kartographie und Geodäsie (2011) as a rather detailed outline including the detailed shapes of individual sea bays, map B shows a moderately simplified version of the outline. Although some of the detail information got lost after simplification, the general outline is still preserved. Map C, however, features a stronger simplification that even omits visualizing the outlines of some of the smaller bay structures. While being less useful for showing details of the coastal structure, this kind of representation might be useful for visualization at larger scales. Therefore, it is important to carefully select the level of modification applied to the data that supports understanding the communicated information, instead of adding confusion.

A B C

Figure 2.7: Different levels of simplification of the outline of the German State of Schleswig-Holstein: A = original outline data, B = moderate simplification, C = strong simplification. Map data from OpenStreetMap.

One drawback of the original version of the Douglas-Peucker algorithm is that it not always accounts for preserving non-self-intersection for the output curve. Hence, various researchers attempted to improve the effectiveness of the algorithm, while anticipating satisfactory generalization results for any shape of input curve.

Notable adaptions of the Douglas-Peucker algorithm have been proposed with regard to avoiding self-intersection of the output curve. Given the original version of the algorithm, it is not always possible to avoid self-intersection of complex line structures, particularly, in case a large ε value is chosen. Wu and Marquez (2003) present an adaption of the original Douglas-Peucker algorithm using star-shaped regions that applies slight modifications in the way that a splitting vertex is chosen at each refinement iteration. Further adaptions mainly concern the improvement of the running time of the algorithm. Hershberger and Snoeyink (1994), for example, present an adaption that, using path hulls, instead of a quadratic worst case run achieves an improved running time of $O(n \log n)$.

Displacement

In digital cartography, the displacement operation plays a central role, particularly, when there is a need to avoid overlap of different map objects when adapting a map representation to various zoom levels. Since the displacement of a map object often also requires changing the position of neighboring objects in order to preserve the original topology, holistic approaches that automatically optimize the map representation for the whole scene provide an effective and convenient way for map-makers when dealing with spatial overlap (Sester, 2005).

An example of such a holistic displacement approach has been proposed by Sester (2006) when introducing *PUSH*, which is a software program developed for automatically generalizing cartographic objects, particularly for resolving spatial conflicts by means of displacement. The program allows to describe the behavior of objects during the process of displacement very flexibly by defining various parameters, for example the allowed degree of deformation of an object or the minimum space required by an object.

The following three parameters are required for performing the displacement procedure:

1. *Aura*
   The parameter *aura* describes the minimum distance (in meters) that an object should keep from its neighbors).

2. *Stiffness*
   The parameter *stiffness* describes the rigidity or deformability of an object. The parameter takes values between 0 and 1, while the value 1 relates to a very stiff object, for which deformation should be minimized, and a smaller value allows for a stronger deformation.

3. *Pushable*
   The parameter *pushable* describes the movability of an object. The parameter accepts values between 0 and 1, while a value of 1 means that the object is intended to remain at the original location (as little shift as possible), and a small value allows the possibility of shifting.

These parameters need to be added in the attribute table of a shapefile to be generalized, before executing the program. The parameters can be specified for each object individually. The software reads vector data, which is prepared in ESRI shapefile format.

Once the map objects which have to be displaced are assigned the previously mentioned parameters, the global optimization finds a holistic solution, taking all the other objects into account, i.e. displacing them appropriately, if needed. As the whole scene is treated in one optimization process, it is possible to also define larger values for the *aura* parameter for the corresponding map object. This displacement of map objects can be very useful for visually establishing a clear distinction between different road objects in a road network.

The automatic procedure PUSH involves several parameters that need to be specified: 1) the number of iterations for achieving optimal results, 2) the general minimal distance between all objects (if value = 0, then only object-specific *aura* values are used), 3) the critical distance from which objects are moved towards each other instead of being displaced (value = -1, if displacement should always be applied), and 4) the specification of the number of Steiner points to be added as part of a Constraint Delaunay Triangulation to make sure that objects are considered as neighbors for correctly calculating distances between objects.

These parameters are considered during the displacement process in addition to the parameters *aura, pushable* and *stiffness*, which are added as attributes in the object shapefile. As object files, multiple shapefiles that should be considered for the PUSH procedure, can be included at the same time. As a result of the automatic procedure, the generalized objects are again saved in shapefile format.

Figure 2.8 illustrates an example of a displacement operation involving roads (gray colored lines) and rows of trees (green colored lines). In the representation that shows the initial situation (A), it is difficult to visually distinguish the different lines, since some of them partly overlap or are visualized too close to each other. In the representation after optimization (B), however, all objects are clearly visible and distinguishable, which may largely enhance usability of the map.

Figure 2.8: Cartographic displacement using the program PUSH: A = initial situation prior to generalization, B = situation after optimization. The gray lines refer to the road network, the green lines symbolize rows of trees.

Nowadays, many of the previously mentioned cartographic generalization techniques are implemented into GIS software as tools using an automated procedure, which makes it very convenient for the user to apply these methods to the own data.

In this thesis, some of the described existing concepts for cartographic generalization such as polyline simplification or displacement have been used as a basis for developing generalization-based map symbolization techniques for visually communicating effectiveness of route options. The proposed methods using cartographic generalization are described in chapter 5.3 of this thesis.

2.4 Nudging

Many of the decisions a human makes when moving in the environment are assumed to be influenced by the environmental context, but also by systematic biases due to different psychological mechanisms. Therefore, in behavioral economics, the concept of *nudging* attempts to change the subjective perception of the environment in a way that certain desired behaviors occur as intuitively as possible. In this way, the aim is to *nudge* people in a desirable direction, without restricting them in their choice (Mertens et al., 2022). Sunstein (2015) further suggests that an emphasis on welfare, autonomy and dignity can distinguish the principle of *nudging* from *manipulation*. In behavioral economics, a large variety of nudging techniques are used to promote behaviors that are desirable for the individual person or society as a whole. This could for example relate to sustainable consumer behavior, safe road user behavior, or environmentally conscious behavior.

Thaler and Sunstein (2021) define four criteria that must apply in order to denote a behavioral intervention as *nudging*:

1) Predictability of the target behavior: The desired behavior intended to be promoted by the *nudge* is influenced in a predictable way.
2) Voluntariness: The applied measure does not involve any prohibitions, regulations or rules, while a person can freely choose, if the *nudge* is followed or neglected.
3) No financial incentives, penalties or rewards.
4) Ethical justifiability: The applied measure is in the interest of the well-being of the influenced person or society.

There are four main forms of nudging techniques: 1) measures that facilitate desirable behavior or impede undesirable behavior such as *setting default options* or *prompts*, 2) measures that use the social influence such as *focusing on social norms*, 3) measures that modify the context of an action such as *framing* and *priming*, and 4) measures that use emotions or the human play instinct such as *gamification*.

Table 2.3 provides a selection of frequently used nudging techniques and a short description for each technique (Thaler & Sunstein, 2021).

Table 2.3: Selection of frequently used nudging techniques.

Nudging technique	Description
Commitment nudge	Using active and official commitment to a cause for achieving goals
Defaults	A desired action is set or pre-selected as a standard, since keeping the pre-selection causes less effort
Framing	If the same content is presented in different frames, it can lead to a distorted view, and to people reacting differently to it
Gamification	Game-typical elements and processes are transferred to non-game related situations
Optical distortion	Using optical illusions or distortions for drawing a distorted view of the reality for influencing behavior
Priming	A stimulus (e.g. word or picture) arouses associations in the brain. Related contents are immediately recalled and easily remembered, and associated behaviors are performed more easily
Prompt	A behavior is more likely to occur when a corresponding stimulus is provided at the right point in time
Social norm	Communicate a behavior as a social norm, since people tend to orient themselves to the behavior of others

In this thesis, the concept of *nudging* is applied in a way that an appropriate visual communication of traffic or environmental information should get road users to decide for a *societally favorable* route option, even in case this option is not the individually most efficient one (i.e. involving longer travel times). For this, primarily *optical distortion* (symbolization and cartographic generalization) and *framing* techniques are applied, which are explained in more detail in the next sub-chapter. Importantly, the visual communication does not intend to prescribe a specific route to the user, but rather recommend a temporarily favorable route, while still offering the option to actively decide for alternative routes.

Framing in the context of environmental information

For effectively communicating environmental information, it is important to apply a suitable *framing* of the information, since the way how information is framed makes a difference regarding how people think about a problem, make decisions and take actions (Scheufele & Iyengar, 2012). Framing of environmental information is suggested to be most effective when appealing to empathy as well as personal and social responsibility (Lakoff, 2010). Framing effects are commonly related to either *gain framing* or *loss framing*. While *gain framing* describes the case of emphasizing the benefits of the communicated situation, *loss framing* emphasizes a potential negative outcome of the situation. Gain framing is suggested to be generally more suitable for communication of the severity of environmental impacts. Further research in this field (Myers et al., 2012) showed that a public-health focus for framing environmental hazards is likely to elicit emotional responses that support willingness for solving environmental issues. However, previous research in the field of framing indicates that negatively framed information in general has a stronger impact on decision making than positively framed information (Spence & Pidgeon, 2010).

A special case of a loss frame is *fear framing*, which describes a negatively focused loss frame that intends to evoke a more extreme, negative emotional response. Despite its assumed effectiveness for motivating people to a behavior change, it is advisable to handle the use of fear framing carefully, since it could lead to a complete avoidance of the communicated situation.

For a large part of the global population, environmental problems such as climate change or air pollution are a psychologically distant issue. That is, because people may not feel directly affected by the consequences. Hence, emotional responses related to these topics might be relatively weak for some people (Pirani et al., 2020). For making environmental issues more tangible, framing can be used to present them as a more prominent, local and closer issue (Spence & Pidgeon, 2010).

While in literature, framing effects are primarily discussed in the context of verbal or textual descriptions or statements, the concept of framing can also be transferred to visual means of communication, such as graphical illustrations, visual imagery or cartographic maps (Lakoff, 2010).

To investigate the effectiveness of nudging methods for influencing behavior, Mertens and collaborators (2022) conducted a meta analysis of more than 200 studies. It was found that most of the techniques showed small or medium effects. It was also shown that nudging techniques are not equally effective in different areas of the daily life. Another point to consider is that nudging might be less effective for persons who already have a strong personal position towards a specific topic (de Ridder et al., 2022), and hence may ignore any type of behavioral intervention.

2.5 Maps and emotions

In cartography, viewing a map representation is highly related to emotions felt as a response to this interaction. There are two different ways of linking map representations with emotions. Specific emotions can either be intentionally mapped using appropriate symbolization, or they can be felt as a response to viewing a map. It is also possible, and sometimes desired by the map maker that the emotive map in turn evokes emotions in the viewer, which are ideally the desired emotions. A more detailed review of research works dedicated to mapping emotions can be found in chapter 3.4 of this thesis.

2.5.1 Classifying emotions

For classifying emotions, various models have been developed that either define emotions as discrete categories (Harmon-Jones et al., 2016), or describe them based on different dimensions.

Ekman (1992) proposes the definition of a set of basic emotions, which are considered as discrete families that comprise a variety of similar affective states. In this context, combinations of basic emotions are suggested to be considered as blends or mixed emotional states (Ekman & Friesen, 2003; Plutchik, 1991). Early research on dimensional models has concluded that affective states can be described by between six and twelve independent factors of affect that each are treated as separate dimensions. However, other theories suggest that rather than being independent, affective dimensions are interrelated and can be represented by a spatial model that orders affective concepts in a circular space. A prominent example of a dimensional model is the *circumplex model of affect* as proposed by Russel (1980), which suggests emotions being distributed in a two-dimensional circular space, consisting of the two dimensions *arousal* and *valence*.

Figure 2.9 shows a graphical representation of the circumplex model of affect. While the horizontal axis represents the *valence* dimension (pleasant / unpleasant), the vertical axis relates to the *arousal* dimension (activation / deactivation), and the center of the circle represents a neutral valence and a medium level of arousal. Each emotion can be described as a linear combination of the two dimensions (Posner et al., 2005). Hence, emotions can be specified at any level of arousal or valence, or at a neutral level. The proposed arrangement of emotion terms in the circular space with the two axes valence and arousal has been verified by Russel (1980) in four different studies. The validation largely confirmed the expected circular ordering of eight emotion categories (Ross, 1938) by computing polar coordinates for the different affect words. It has been shown that affective space is bipolar, with the two dimensions valence and arousal. However, it has also been shown that emotion terms are spread out continuously around the perimeter of the space, rather than forming clusters around discrete emotion categories.

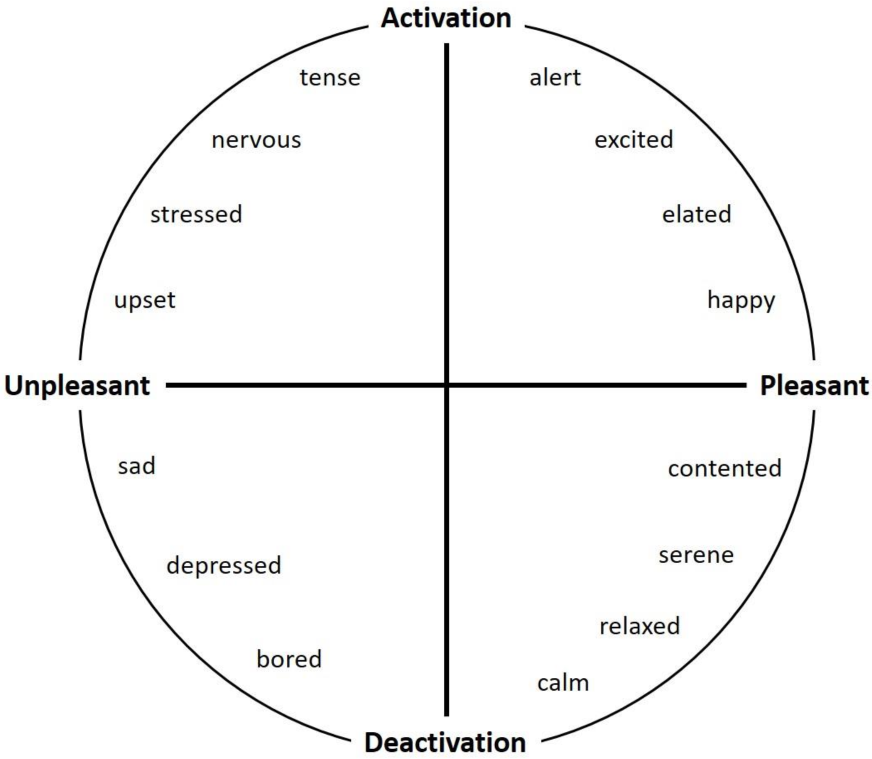


Figure 2.9: Graphical representation of the circumplex model of affect. Adapted from Posner et al. (2005).

2.5.2 Instruments for measuring emotions

Based on the common emotion classifications, various tools or instruments have been implemented to *measure* emotional responses of humans to situations, events or objects.

Most of the developed instruments intend to measure self-reported emotions. Harmon-Jones and collaborators (2016), for example, propose a questionnaire that is sensitive to the eight distinct emotions *anger*, *disgust*, *fear*, *anxiety*, *sadness*, *happiness*, *relaxation*, and *desire*. Other tools attempt to describe and measure emotions based on terms that are distributed on a circular space, as proposed in the earlier described dimensional *circumplex model* by Russel (1980). Examples of these tools are *Plutchik's wheel of emotions* or the *Geneva Emotion Wheel (GEW)* (Scherer, 2005). *Plutchik's wheel of emotions* is based on eight primary bipolar emotions: *joy* and *sadness*, *surprise* and *anticipation*, *fear* and *anger*, *trust* and *disgust*. The different emotion categories include various levels of intensity and can be combined to represent mixed emotions.

The *Geneva Emotion Wheel* (visual example provided in chapter 6.3.4 of this thesis) consists of discrete emotion terms corresponding to 20 basic emotion families that are aligned in a circle based on the two dimensions valence (negative to positive) and control (high to low) (Sacharin et al., 2012). The arrangement of emotion terms on a circle further allows selecting different emotion intensities from low intensity (towards the center of the wheel) to high intensity (towards the outer circle of the wheel). For the case that none of the provided emotion terms matches the users felt emotion, the tool allows selecting the options *no* emotion and *other* emotion, which are placed in the center of the wheel.

A further method for analyzing subjective information such as emotions or sentiments related to a situation is to analyze a person's verbal or textual descriptions as part of a *sentiment analysis*. Various tools have been developed for automatically retrieving the sentiments of a description. Most of these tools are based on a specific emotion lexicon that associates words to a list of basic emotions. An example for this is the *NRC Emotion Lexicon*, which uses eight emotion categories (according to Plutchik) and the two sentiments *positive* and *negative*. The lexicon is based on English language, but also provides translations to various other languages (Mohammad & Turney, 2013). Other tools use emotion lexicons that have been specifically developed for a particular language. Examples for German language adaptions of emotion lexicons are the Affective Dictionary Ulm (Hölzer et al., 1997) that is based on eight emotion categories, and the BAWL-R (Berlin Affective Word List Reloaded) lexicon (Vo et al., 2009), which rates emotion words on the scales *valence* and *arousal*. A particular difficulty that occurs when categorizing emotions or assigning emotions to words is that languages differ in the number of words they provide for a specific emotion or emotion category (Russel, 1991). Also, for a specific word, it might occur that there is no direct equivalent in another language, or the translation might be associated with a slightly different emotional state.

Sentiment analysis is a task within the broader field of natural language processing (NLP) (Nadkarni et al., 2011). NLP-based methods intend to make the contents of written information understandable by a computer, so that any text can be processed and analyzed automatically considering different context information. Among others, further NLP-related tasks include *word segmentation*, *lemmatization* (grouping together inflected forms of a word) to facilitate text analysis or *word-sense disambiguation* (select a meaning of a word that makes most sense in the given context).

2.6 Map-related usability testing

Since the time that the first cartographic representations have been created, map-makers always aimed to use maps for effectively communicating the depicted spatial information to the map-reader. The challenge, however, is to present the spatial information in an understandable, visually appealing, and appropriate format, so that both professionals and novices can make use of it. To achieve this, it is important to test the usability of design proposals for map representations. For assessing the usability of a map representation, evaluation methods can either test subjective or objective criteria (Wielebski, & Medyńska-Gulij, 2019). Subjective usability testing usually comprises criteria such as user-perceived effectiveness, graphical attractiveness, intuitiveness, or the estimated suitability of a visualization for representing the communicated phenomenon. Objective criteria can comprise measuring the effectiveness and efficiency of a visual representation for achieving a certain goal. While effectiveness often corresponds to the error rate (response accuracy), a common way of assessing efficiency related to visual representations is to measure the decision time (response time) related to a map-based task (Wielebski, & Medyńska-Gulij, 2019).

Each usability test tries to verify assumptions made related to the tested variables. Since these assumptions are expected to be based on the state-of-the-art in the corresponding field of research, a set of hypotheses needs to be developed. In empirical science, a scientific hypothesis is a statement made prior to conducting the experiment, whose correctness is verified based on the findings of the conducted research.

2.6.1 Types of user study designs

The most common form of usability testing in the context of map design is to conduct a user survey involving human participants. Depending on the research question, the target user group, or the number of tested conditions, the dimension of such an experiment could range from small surveys with only a few participants, to large-scale studies involving thousands of participants.

Nowadays, there are different possible ways of interacting with participants in a user study. The most commonly applied types are either on-site experiments or online surveys. While an on-site experiment is usually more difficult to arrange and more time-consuming, the participant’s actions and behavior are easier to be controlled by the experimenter. For online experiments, however, chances are higher to get a sufficient sample with a large number of participants, since the survey tasks are easily accessible from different locations. At the same time, the risk is also higher that a participant would not complete the experiment. Furthermore, this type of experiment requires a very careful study design. As it is usually not possible to provide clarifications to participants during an online experiment, tasks need to be clearly described in the survey materials.

The anticipated number of participants or sample size (*n*) depends on the design of the study. In case the sample size is chosen as too small, it may not be possible to statistically verify the hypotheses. A too large sample size, however, may lead to a waste of resources, in case fewer participants could have been sufficient for verifying the hypothesis. The sample should be selected based on the intended user group of the tested visualization. In case the entirety of the user population is addressed and results intend to be generalizable, the sample should comprise participants from all intended user groups. A reasonable sample size is possible to be calculated in advance for a particular study design. One approach could be to calculate the statistical power of the study by estimating the effect size based on pilot study results or similar, previous works in the field (Sullivan & Feinn, 2012). A more systematic way to estimate power is to conduct a power analysis. Statistical power is the probability of finding a true effect when a result has been found statistically significant. A power analysis can be performed before (a priori) or after (post-hoc) data collection. While an a priori power analyses provides information about the number of participants to recruit for achieving a desired level of statistical power, a post-hoc power analysis provides information about the sensitivity of data to detect a range of effect sizes. In this thesis, power analysis was performed for user study 3, in order to verify that the sample size was appropriate for performing an ordinal regression analysis (Whitehead, 1993).

When intending to compare several different conditions as part of the same user study, two types of study designs are distinguished: A *between-subjects* (or between-groups) study design, and a *within-subjects* (or repeated-measures) study design (Hemmerich, 2022). In the *between-subjects* design, each person is only exposed to a single user interface, while different participants are assigned to different conditions corresponding to a variable. The advantage of this type of design is that it reduces learning effects and results into shorter sessions, which might be less tiring for the individual participant. *Within-subjects* (or repeated-measures) design requires the same participant to test all conditions or user interfaces corresponding to a variable. Advantages of this method are that fewer participants are required and random noise is minimized. However, to avoid order effects, randomization regarding the order of showing the different conditions, is required.

In addition to these two common types of user study designs, there is also the option of preparing a more complex, *mixed-design* user study that combines characteristics of both between and within-subjects designs (Quiroz et al., 2018). This is for example the case, if different user groups are defined, but within each user group, participants are performing the same set of tasks.

Each user study typically involves different types of variables that are defined by the experimental design. They are either *independent* or *dependent* variables. An independent variable is controlled or manipulated by the researcher and can for example relate to visualization type, user type, time, gender, age or scenario. A dependent variable is a measured value (e.g. rating result) and expected to vary as a result of the independent variable manipulation. Additionally, in contrast to a *fixed factor*, a *random factor* can be introduced (such as *participant*), in case for this factor not all levels of interest have been measured. In case the analysis produces statistically significant results, it can be concluded that a change in the independent variable *caused* a change in the dependent variable.

Tools for conducting user surveys

As described above, there are different ways of carrying out a user survey including on-site experiments and online surveys. For online surveys, there are various tools available that facilitate preparing the questionnaire according to the study design. For the research described in this thesis, two different tools have been used: *Unipark* (license from TU Braunschweig) (UNIPARK, 2023) and *LimeSurvey* (license from LUH) (LimeSurvey, 2023). Both tools are specialized in online surveys and provide similar functionalities. In both cases, the user interface of the software allows the user to create various different surveys. For each survey, there is the option to choose between several templates for different types of questions and responses. However, there is also the option to integrate CSS code for adapting the styling of a question to the user's requirements. The software further supports randomization of variables in the survey and allows to define different user groups in the settings. Once the survey is prepared, an access link can be shared with potential participants. Furthermore, a data file including the raw data of the participants' responses can be retrieved in different formats such as *CSV* or *Microsoft Excel*, but also files that can directly be used in statistical analysis software such as *SPSS* or *R*.

2.6.2 Statistical analysis of user survey results

Usually, the choice of the experimental design already specifies the types of statistical analyses that need to be applied to the data for adequately answering the research question. This sub-chapter provides an overview of different types of statistical analyses that are commonly applied in the context of analyzing user survey results, while specifically focusing on analytical methods that are applied as part of this thesis. The sub-chapter first introduces some basic statistical concepts such as descriptive statistics, while in the further course, different tests for assessing statistical significance are described, along with effect size measures for estimating the statistical power of an observed effect.

2.6.2.1 Descriptive statistics

Before continuing with more specific types of analyses, it is useful to first get an idea about the general distribution of the data. For estimating central tendencies and dispersion in the data distribution, a common procedure is to retrieve descriptive statistics of the dataset (Fisher & Marshall, 2009). Descriptive statistics as a basic statistical concept facilitate understanding the characteristics and the degree of dispersion of values in the dataset, and therefore can provide useful information for deciding how to proceed in data analysis. Commonly used measures for estimating central tendencies are the *arithmetic mean*, *median* (middle value in dataset) and *mode* (most frequent value in dataset). While the arithmetic mean is commonly used for describing central tendencies of continuous data, the median is often a more suitable measure for describing ordinal data, since the median is more robust to outliers. The mode provides information on the frequency of a value in the dataset and is often used in relation to nominal data. In addition to calculating the *arithmetic mean*, there are various other approaches for determining a mean value, such as the *harmonic mean* or the *geometric mean*. In this thesis, only the *arithmetic mean* is applied; hence, in the further course of the thesis the term *mean* is used, which always refers to the *arithmetic mean*. When reporting statistical results, the mean is commonly denoted using the abbreviation *M*. Moreover, it is possible to calculate a weighted *arithmetic mean*, by adding weights to the different values to specify the impact of a value on the calculation results.

When describing the data collected in a sample, a value of dispersion should be reported in addition to the central tendency value. Among others, measures of dispersion comprise *standard deviation, variance*, *kurtosis* (deviation of the actual distribution from the normal distribution), *skewness* (asymmetry of the probability distribution), *quantiles* (number of values of a distribution above or below a certain limit) and *range* (deviation between largest and smallest value of a sample).

The most commonly reported measure of dispersion is the *standard deviation*, which describes the amount of variation of a set of values. While a high standard deviation indicates that data values spread over a wide range, a low standard deviation suggests the values being located close to the mean. In statistics, the standard deviation of a sample is equal to the square root of its variance. The standard deviation *s* is commonly reported using the abbreviation *SD*.

A related measure is the *standard error* of the mean, which is the standard deviation of its sampling distribution (repeated sampling from the same population) or an estimate of that standard deviation, and equals the standard deviation divided by the square root of the sample size. In that way the standard error is a measure of dispersion of sample means around the population mean. Different from the standard deviation, the standard error is not a descriptive statistic, but a descriptive of the random sampling process.

The type of measure to report depends on which type of variable the data is associated with. The collected data can either be in a categorical or continuous format (Marshall & Jonker, 2010). Categorical data can be classified into binary, nominal and ordinal data. While for binary data, only two different resulting values are possible (e.g. *yes* and *no*), nominal data can be assigned to a discrete number of more than two possible values. In both cases, data can be represented by assigning data values to categories. The measure of central tendency related to binary or nominal data is the mode, which describes the category comprising the most cases.

Another categorical type of data relates to an ordinal data format. Ordinal data frequently results from ratings using a Likert Scale, for example for categorizing the level of agreement with a certain test condition (Joshi et al., 2015). While different numbers of rating categories are possible, 3-, 5- or 7-point Likert scales are most common. A typical format of a 5-point Likert scale could be structured as follows: 1) strongly disagree, 2) disagree, 3) neutral / no preference, 4) agree, and 5) strongly agree. An uneven number of rating categories allows the survey participant to take a neutral position on a question, while an even number of categories forces the participant to decide for a specific point of view. Due to the bipolar character of the scaling method, Likert scales measure both positive and negative response to a statement, while an equal number of positive and negative rating options should be provided to ensure symmetry of the rating scale and avoid a bias towards either a positive or negative rating. For ordinal data, the middle of the set of numbers (median) is typically used as the measure of central tendency. However, in case a Likert scale is symmetric with an assumed equidistant arrangement of items, it can approximate an interval-level measurement, and thus the calculation of the mean provides an alternative way of describing the central tendency. This approach is for example followed when describing the Likert scale data obtained from the route choice tasks in *user study 2* and *user study 3* (chapter 6), as well as for the intuitiveness and suitability rating in *user study 1*, in order to provide more precise information regarding the differences between the variables.

Continuous data formats are represented by interval- or ratio-scaled data. The difference between both types of data is that ratio data has a true zero value, while interval data does not have a true zero value. The central tendency of continuous data is commonly described by the mean. In case the data is not normally distributed, reporting the median could be a useful alternative.

A frequently used way of visualizing the distribution of data is a boxplot (Frigge et al., 1989). A boxplot usually shows the minimum (lowest data point in dataset excluding outliers), the maximum (highest data point in dataset excluding outliers), the median, the first (or lower) quartile (median of the lower half of the dataset, and the third (or upper) quartile (median of the upper half of the dataset). The distance between the upper and lower quartiles that forms the box in the plot is denoted as the interquartile range. This range comprises of 50 percent of all values in the dataset. Outliers referring to individual data points are visualized beyond the line that marks the minimum or the maximum.

Outliers

When preparing the data for statistical analysis, it is important to perform a data cleaning step before applying any statistical test, to ensure that the used data is valid. Outliers in a dataset are usually values that are located outside the *normal* range of values for a specific variable. Which values are considered as *normal* may depend on prior knowledge related to the measured variable. The occurrence of outliers can be due to various reasons, including measurement errors, data preprocessing errors, or unusual behavior of participants. There are different methods for detecting outliers in a dataset, ranging from solely visual methods to more sophisticated methods using machine learning. A simple way of visually detecting outliers is to create histograms of the data distribution or a boxplot as described above. Another method is to calculate the *z-score* for identifying the distance of a data point from the mean.

Similar as for their detection, there are different ways of handling outliers. The most straight-forward way might be to simply remove the values identified as outliers from the dataset or remove the entire data of the test person the outlier value is related to. Another option is to replace the values of each outlier by another value that corresponds better to the range of data. This value could for example be the mean of the sample data. Yet another option is to retain the outlier values in the dataset and perform a non-parametric test on the dataset.

Normal distribution

Since various statistical tests such as t-tests, linear regression or Analysis of Variance (ANOVA) assume the data being normally distributed, it is important to test for normality beforehand. A *normal distribution* (also referred to as *Gaussian distribution*) is a continuous probability distribution for a random variable (Johnson et al., 1987). Normally distributed data is characterized by a typical *bell curve*. The general form of its probability density function is described as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (2.1)$$

, with

μ = mean of the distribution

σ = standard deviation of the distribution

Figure 2.10 illustrates the probability density function with variations in mean and variance. The red curve represents the standard normal distribution as the simplest case of normal distribution, with $\mu = 0$ and $\sigma^2 = 1$.

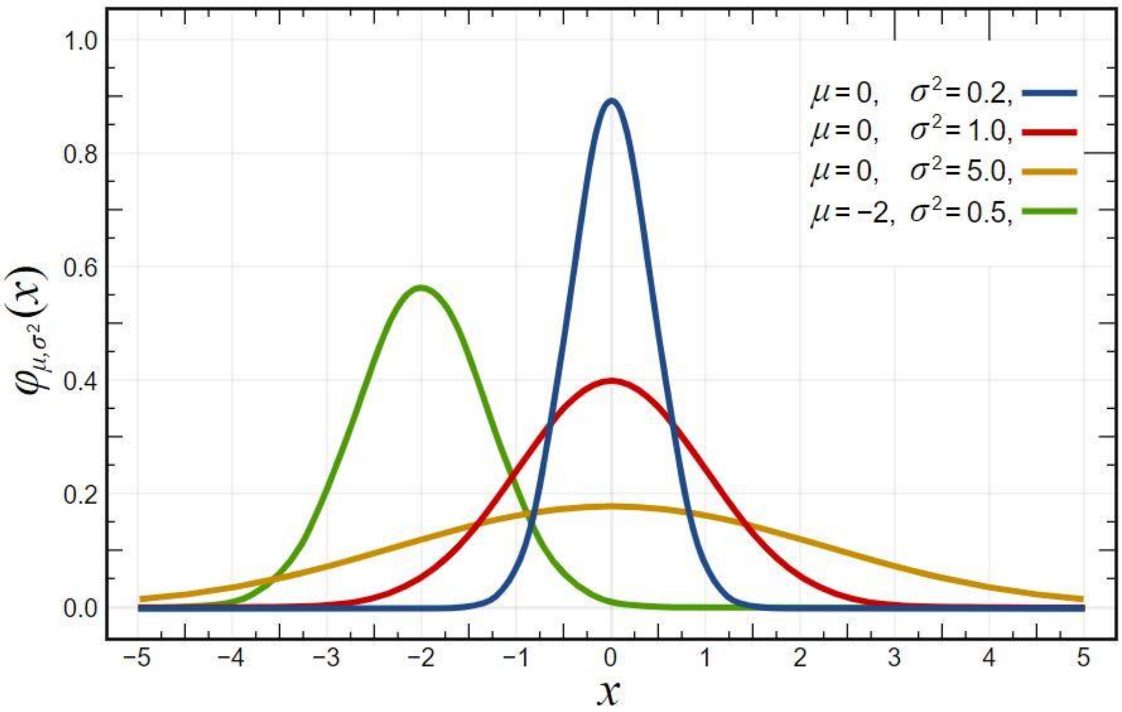


Figure 2.10: Visual representation of the probability density function with variations in mean (μ) and variance (σ^2).

Common procedures for assessing, if a random sample follows a normal distribution are graphical methods such as boxplots, histograms and Q-Q-plots, numerical methods such as skewness and kurtosis indices, and formal normality tests (Razali & Wah, 2011). Examples for normality tests are the *Shapiro-Wilk* test, the *Kolmogorov-Smirnov* test, the *Lilliefors* test and the *Anderson-Darling* test. However, power analysis using Monte Carlo simulation has found that the different tests differ in power, while the *Shapiro-Wilk* test has been found most powerful (Razali & Wah, 2011).

Normality tests verify, if a sample comes from a normally distributed population, and are frequently used for model selection – more specifically for facilitating the selection of the appropriate statistical model to be used. Due to their bipolar format, Likert type data frequently resulting from user surveys usually do not follow a normal distribution. Instead, this type of data typically shows each one peak for agreement and disagreement, and fewer responses for a neutral position.

2.6.2.2 Basic statistical tests and models

In general, statistical tests can be classified into *parametric* and *non-parametric* tests (Sheskin, 2003). Parametric statistics assume the information about the distribution of the population to be known and based on a fixed set of parameters. In non-parametric statistics, however, information about the population's distribution is unknown and parameters are not fixed. Although parametric tests are often considered to be statistically more powerful than non-parametric tests, they might not be applicable for data analysis in case some particular assumptions are not met. These assumptions include the data being numerical, normally distributed and the variance between groups being homogeneous. For non-parametric tests, however, most of the assumptions made for parametric tests do not apply.

For most of the commonly used parametric statistical tests, a non-parametric alternative is available, which can be applied, if the above mentioned assumptions for a parametric test are not met. Among other factors, the level of measurement of the dependent variable can be used as an indicator for deciding, if a parametric test can be applied, or if a non-parametric alternative is more suitable. Parametric tests are usually applied when the dependent variable is numerical and measured on a continuous scale. In case of a categorical (nominal) or ordinal level of measurement of the dependent variable, a non-parametric test is typically the more appropriate choice. Advantages of a non-parametric test are that they can also be applied to smaller sample sizes, and – different than parametric tests – can be used for all types of data. This means that a non-parametric test can also be applied to continuous data that meets all assumptions for a parametric test, however, in this case, statistical power is expected to be weaker.

In the following, several statistical tests and models are presented that are commonly used for investigating differences between different variables, when analyzing user survey data. Table 2.4 summarizes a selection of different tests that are frequently applied in statistical analysis – depending on the data setup. If applicable, for each parametric test, the non-parametric equivalent is provided.

Table 2.4: Overview of frequently used parametric tests and their non-parametric alternatives.

Data setup	Parametric (continuous data)	Non-parametric (categorical data)
2 Groups Between-subjects	Independent samples (unpaired) t-test	Mann-Whitney U test
2 Groups Within-subjects	Dependent samples (paired) t-test	Wilcoxon signed-rank test
> 2 Groups Between-subjects	Analysis of Variance (ANOVA)	Kruskal-Wallis test
> 2 Groups Within-subjects	Repeated measures ANOVA	Friedman test
Correlation	Pearson correlation (r)	Spearman correlation (ρ)

When investigating differences between groups, the most frequently used parametric tests are the independent samples t-test and the Analysis of Variance (ANOVA). While the independent samples t-test tests for differences in a continuous dependent variable between two groups, the ANOVA is applied accordingly in case there are more than two groups to be compared. The non-parametric alternative to the independent samples t-test is the Mann-Whitney U test, which is for example used in case the dependent variable is measured on an ordinal scale. In case the parametric assumptions are not met for performing an ANOVA, the Kruskal-Wallis test can be used as a non-parametric alternative. The type of ANOVA described in this context relates to a one-way analysis of variance, which considers the influence of one independent variable on a dependent variable. In case the influence of two different independent variables on one dependent variable is observed, a two-way ANOVA needs to be applied. In case of ordinal data, a non-parametric alternative that allows testing the influence of two independent variables is ordinal regression (two-way repeated ordinal regression), which is explained later in chapter 2.6.2.3.

In case of a within-subjects or repeated-measures design, the most appropriate parametric statistical procedures for testing differences in a continuous dependent variable among one group over a period of time (or over different test conditions), are the dependent samples (paired) t-test and the repeated measures ANOVA. The dependent samples t-test compares scores at two different points in time, while the repeated measures ANOVA is suitable in case more than two points in time or test conditions are considered. The non-parametric version of the dependent samples t-test is the Wilcoxon signed-rank test, while the non-parametric equivalent of the repeated measures ANOVA is the Friedman test. In both cases, the non-parametric tests are usually applied to ordinal scaled data that not necessarily follow a normal distribution. In this thesis, for example, the Wilcoxon test is used for investigating differences in route choice measurements before and after map modification.

For examining the strength of association between two continuous variables, a frequently used parametric test is the Pearson correlation (r). In case at least one of the variables is measured on an ordinal scale, the Spearman correlation (ρ) as the non-parametric equivalent to the Pearson correlation is the more appropriate choice. The Spearman correlation is based on the statistical dependence between the rankings of two variables.

A further commonly applied statistical hypothesis test is the chi-squared test, which is used to test whether two categorical variables are independent in influencing the test statistic.

2.6.2.3 Sophisticated statistical models for non-parametric data

While the previously described approaches for analyzing parametric or non-parametric data such as the Dependent samples t-test or the Wilcoxon signed-rank test are suitable for analyzing data with a single predictor (independent variable), including additional predictors may require the definition of a more sophisticated statistical model, such as a regression model. Regression models try to explain an observed dependent variable by one or several independent variables.

Depending on the type of data used for analysis, there are different types of regression models that can be defined. In case of a continuous dependent variable, a linear regression model might be chosen, while in case of categorical data, multinomial logistic regression can serve as an appropriate model. A special case of multinomial logistic regression is binary logistic regression, where the dependent variable is binary.

In case the dependent variable is ordinal, an ordinal regression model needs to be defined. There are three different types of ordinal regression models: The adjacent category model, the sequential model and the cumulative link model (CLM) (Christensen, 2015). In case the model is based on a mixed design and therefore should additionally account for multiple observations within each participant, a cumulative link mixed model (CLMM) has to be defined, which includes both fixed (group) effects and random (individual) effects. An advantage of applying ordinal regression models is that they also account for additional predictors, while non-parametric tests such as the Wilcoxon signed-rank test only account for a single predictor. The significance of the effects of independent variables is tested with an *analysis of deviance (ANODE)* procedure. This approach is similar to the analysis of variance (ANOVA) in linear models. In this thesis, the CLMM is used to examine the effect of two different predictors on route choice decision making (e.g. chapter 6.3.6.1).

2.6.2.4 Statistical significance

Statistical significance in a user survey is typically addressed by conducting statistical hypothesis testing. In general, statistical significance is referred to as a measure of whether the research findings are meaningful. More specifically, it is a measure of the probability of a *null hypothesis* being true compared to the acceptable level of uncertainty regarding the true answer (Tenny & Abdelgawad, 2022). The null hypothesis suggests that there is no statistical relationship between the tested variables. Therefore, the aim is to reject the null hypothesis, while accepting the alternative hypothesis stating that there is a statistically significant relationship between the tested variables. When testing the null hypotheses *H0* against an alternative hypothesis *H1*, the *p*-value is defined as the probability that a test statistic is as extreme as or more extreme than its observed value (Benjamin et al., 2018).

A result is statistically significant based on a predefined threshold *alpha*, if the *p*-value is smaller than alpha, while a *p*-value larger or equal to alpha describes a not statistically significant result. In case the alpha is set to 0.05 and $p <$ alpha, it can be concluded that there is a 95 % chance that the null hypotheses can be rejected, and a 5 % chance that the null hypothesis is true.

Importantly, a statistically significant result cannot prove that a research hypothesis is correct, since statistical hypothesis testing does not assume 100 % certainty, as there is still a slight probability that the results occurred by chance and the null hypothesis was correct. Rather, statistical significance can provide supportive evidence for the research hypothesis being true.

The choice of a suitable threshold *alpha* for defining statistical significance can be made based on different factors such as the field of research, the experimental design, the sample size or the hypothesis. While in some research domains such as high-energy physics or genomics (Benjamin et al., 2018), there is a standardized recommendation for the choice of the alpha level, in many other domains there is no fixed recommendation. Hence, a commonly accepted threshold value for defining statistical significance is alpha = 0.05. Since in the field of cognitive psychology, there is to date no fixed standard concerning significance threshold, in this work, the threshold used for defining statistical significance is set to *alpha* = 0.05 – according to the commonly accepted threshold value.

Significant results are usually marked with an asterisk and printed bold, in order to visually emphasize these values over other non-significant results. By convention, the marking differs depending on the magnitude of significance. A slightly significant result is marked with one asterisk (<.05*), a moderately significant result with two asterisks (<.01**), and a highly significant result with three asterisks (<.001***).

When reporting significance, usually not only the *p*-value is reported, but also further test statistics that differ depending on the applied test. For reporting significance related to an ANOVA or regression analysis, for example, an *F* statistic is reported that describes, if the variance between the means of two populations is significantly different.

2.6.2.5 Main effect and post-hoc tests

In statistical analysis, a main effect describes the effect of one individual independent variable on the dependent variable. Hence, in case the study design involves multiple independent variables, different main effects can be calculated. Additionally, interaction effects can occur, in case there is an interaction between two or more independent variables that affect the dependent variable.

Importantly, main effects for different independent variables can turn out being significant without their interaction having a significant effect. In turn, it is possible that an interaction effect is found, without the corresponding main effects being significant.

While a statistically significant main effect provides information about the existence of significant differences within a group of different means (at least two groups being statistically different from each other), no information is provided regarding which of the groups differ. Therefore, in case of a significant main effect, post-hoc tests need to be performed after running a test that examines the influence of more than two groups within an independent variable on a dependent variable (e.g. ANOVA or Kruskal-Wallis test) to evaluate differences among specific means. Hence, post-hoc tests provide information about which pairs of mean values of the tested groups differ significantly from each other by calculating multiple pairwise comparisons.

There are various different post-hoc tests that differ among the criteria related to the data, such as the equality of the number of observations in different groups or the homogeneity of variance among groups. The type of post-hoc test to be performed further depends on the statistical test that has been applied to the data. Examples of post-hoc tests that can be applied after running an ANOVA are *Bonferroni* (using t-tests to perform pairwise comparisons between group means) or the *Tukey HSD* test using range statistic to perform pairwise comparisons between all possible pairs of groups. An example of a post-hoc test that can be applied after a significant main effect of a non-parametric test is the *Dunn-Bonferroni* test, which can for example be applied after running a Kruskal-Wallis test.

When reporting pairwise comparisons, measures to be reported are commonly the *p*-value for significance, the difference between means, and the standard error.

2.6.2.6 Effect sizes

While statistical significance provides information concerning whether an effect has been found or if findings are due to chance, the *effect size* describes the magnitude of the difference between groups and therefore allows estimating the strength of a statistically significant result. Both measures provide information that is relevant to be reported for readers to understand the full impact of the research findings (Sullivan & Feinn, 2012). However, according to Cohen (2016), reporting the effect size of a finding as a measure of magnitude has much more practical importance than solely indicating statistical significance of results expressed by the *p*-value. This means, a statistical test can result into a statistically significant difference, even though no effect has been found. This is particularly possible, in case the alpha value for significance is set too large, or in case of a very large sample size. Different from statistical significance, effect size is independent of sample size.

While reporting effect sizes is important for estimating the impact of research findings, there is no measure that can be used universally for different statistical tests. Rather, effect size is estimated with different indices, depending on the type of statistical analysis that is performed.

Table 2.5 summarizes a selection of several different commonly applied effect size indices, which are each suitable for different types of statistical tests (Sullivan & Feinn, 2012; Cohen, 1992; Cohen, 2016). There are two main categories of indices for effect sizes: Between group differences and measures of association between variables. For each index, the table provides a description, threshold values for effect size and examples of statistical tests for which the index is suitable. While the description clarifies how the index is calculated, threshold values of effect size are provided for defining small, medium or large effect size.

The most commonly used effect size index is Cohen's *d*, which is a measure of the standardized difference between means of two groups frequently used for estimating effect sizes based on t-test or ANOVA results. The requirement here is that both groups have the same size. In case the standard deviations of the two groups differ to a larger extent, it is recommended to use the standard deviation of the control group instead of the pooled standard deviations of both groups. The adjusted effect size measure is called *Glass' Delta.* It is also possible to transform Cohen's *d* into other effect size measures such as the correlation coefficient *r*. Another frequently applied way of measuring effect size based on an ANOVA is the Partial Eta-squared (η^2), which measures the proportion of variance associated with one or more main effects.

The *odds ratio* describes the strength of the correlation or independence of two binary coded variables and is often calculated as the effect size measure for binary logistic regression. More specifically, the odds ratio makes a statement about the extent to which the presence or absence of a characteristic A is related to the presence or absence of another characteristic B. Similarly, the risk ratio describes the ratio of risk of an event in one group compared to the risk of the event in the other group.

Cohen's f^2 is appropriate for calculating the effect size within a multiple regression model in which the independent variable and the dependent variable are both continuous (Selya et al., 2012).

The Pearson correlation coefficient r is a measure of the degree of the linear correlation between two at least interval scaled sets of data. The correlation coefficient is calculated as the ratio between the covariance of two variables and the product of their standard deviations. Hence, it is a normalized measurement of the covariance that always results in a value between −1 and 1.

The R^2 coefficient of determination is a statistical measure in a regression model that indicates how well the data fit the regression model (the goodness of fit) and describes the proportion of variance in the dependent variable that can be explained by the independent variable.

While for linear regression models, the described effect size measures are widely accepted, for ordinal regression models, there is no effect size measure that is commonly accepted in statistics. Hence, in literature, a wide range of different measures are used.

Table 2.5: Common effect size indices[1].

Index	Description	Effect Size	Statistical Test (examples)
Between groups			
Cohen's *d*	$d = M_1 - M_2 / s$ $M_1 - M_2$: difference between the group means s: pooled standard deviation	Small: .2 Medium: .5 Large: .8	t-test, ANOVA
Odds ratio (OR)	$\mathrm{OR} = \frac{\text{Group 1 odds of outcome}}{\text{Group 2 odds of outcome}}$ If OR = 1, the odds of outcome are equally probable in both groups	Small: 1.5 Medium: 2 Large: 3	Binary logistic regression
Relative risk or risk ratio (RR)	Ratio of probability of outcome in group 1 vs. group 2 If RR = 1, the outcome is equally probable in both groups	Small: 2 Medium: 3 Large: 4	Logistic regression
Partial Eta-squared (η^2)	$\eta^2 = \frac{SSeffect}{SSeffect + SSerror}$ SS: sums of squares	Small: .01 Medium: .06 Large: .14	ANOVA
Cohen's f^2	$f^2 = \frac{R^2}{1 - R^2}$ R^2: proportion of variance accounted for	Small: .02 Medium: .15 Large: .35	Regression analysis, F-Test
Measures of association			
Pearson's *r* correlation	Range: -1 to 1	Small: ± .2 Medium: ± .5 Large: ± .8	Linear regression
R^2 coefficient of determination	Range: 0 to 1; usually in percent	Small: .04 Medium: .25 Large: .64	Regression analysis

2.6.2.7 Inter-rater reliability

Some methods in empirical research involve subjective assessment of survey results, which could for example relate to assignment of data (such as statements) to different categories. To achieve a more reliable, objective assessment, two or more experts (raters) could assess the same data independently. Afterwards, it can be

[1] Adapted from Sullivan & Feinn (2012)

examined to which extent the rating results are independent of the rater. This procedure is called *inter-rater reliability*.

Cohen's Kappa coefficient can be used to calculate the inter-rater agreement of two raters for categorical items and estimate reliability of the ratings (McHugh, 2012). In case of more than two raters, Fleiss' Kappa is calculated, which is an extension of the Kappa statistic calculation.

The following Table 2.6 shows an example of a categorization made by two raters (based on real data from a user study as described in chapter 6.3.6.8), indicating the frequencies of assigning the observations to (in this case) three different categories. The number of categories may vary depending on the data. Row and column marginals describe the sum of observations assigned to a category by a rater.

Table 2.6: Sample data for calculating Cohen's Kappa.

Rater 1 (R1)

Rater 2 (R2)		C1	C2	C3	Row marginal
	C1	16	3	0	19
	C2	6	96	1	103
	C3	0	0	4	4
	Column marginal	22	99	5	126

Cohen's Kappa (*k*) is calculated using the following formula:

$$k = \frac{p_0 - p_e}{1 - p_e} \quad (2.2)$$

, where

p_0 = relative observed agreement among raters

p_e = hypothetical probability of chance agreement

p_0 is calculated by summing up the cases with agreements among both raters for the different rating categories, divided by the total number of observations n (in the example n = 126).

For calculating p_e, the column marginals (rater 1, e.g. R1C1) multiplied with the row marginal (rater 2), divided by the number of total observations is calculated for each category and summed up, and then divided by the total number of observations.

$$p_e = \left(\frac{\mathrm{R1C1} * \mathrm{R2C1}}{n} + \frac{\mathrm{R1C2} * \mathrm{R2C2}}{n} + \cdots + \frac{\mathrm{R1Cx} * \mathrm{R2Cx}}{n}\right) / \, n \quad (2.3)$$

, where

R = rater

C = rating category

n = total number of observations

x = total number of categories

Following the calculation procedure, for the provided sample data, the resulting Kappa coefficient is k = 0.76. According to Landis & Koch (1977), this value would describe a substantial agreement. Threshold values for defining the strength of agreement for the Kappa statistic are provided in Table 2.7. A complete agreement among raters would result in a Kappa value of 1, while no agreement results in $k \leq 0$.

Table 2.7: Estimation of relative strength of agreement for the Kappa statistic according to Landis & Koch (1977).

Kappa statistic	Strength of agreement
< 0.00	Poor
0.00 - 0.20	Slight
0.21 - 0.40	Fair
0.41 - 0.60	Moderate
0.61 - 0.80	Substantial
0.81 - 1.00	Almost perfect

2.6.2.8 Software for statistical analysis

For performing statistical analyses, numerous software solutions have been developed that support analysis of user survey data. SPSS, R, and Stata are among the most frequently used software for performing statistical analysis in social and natural sciences. In addition, it is also possible to use Python using libraries such as NumPy and SciPy for calculating statistics.

SPSS in a software platform developed and maintained by IBM, which allows to store, preprocess and analyze different types of datasets. SPSS provides a user interface with a large number of functionalities that facilitate defining parameters for running statistical tests. The software *R* is a more programming-focused way of performing statistical analyses. *R* provides a wide range of packages that can be used depending on the statistical test to perform.

For the statistical analysis performed as part of this thesis, the software SPSS and R have been used predominantly.

3 Related work

This chapter provides an overview of previous research work that is related to the topic of this thesis, while focusing on several works that particularly contributed to shaping the topic. While at first, visual route communication using visual variables is discussed, in a next step, relevant works regarding the use of cartographic generalization techniques for symbolizing route information are presented. Afterwards, possibilities for map-based visualization of environmental hazards are evaluated, followed by discussing the role of emotions in map-based communication.

3.1 Visual route communication using visual variables

Cartographers use a large variety of map symbols to emphasize relevant parts of a map while de-emphasizing other parts. Bertin (1967) defined a set of fundamental graphical variables (*location, size, shape, color hue, color value, orientation,* and *texture*), which has been extended over time by adding further variables such as *color saturation* (Morrison, 1974), *crispness, resolution* and *transparency* (MacEachren, 1995). The latter three variables were introduced with the emergence of digital map production methods and are frequently used for mapping uncertainty information. In terms of route maps, uncertainty visualization could help symbolizing the level of favorability in map objects. Among the most commonly used types of visual variables for representing linear features for route-based data are the variables *color hue, texture,* and *size* (Bertin, 1983; Kubíček et al., 2017). Stachoň and collaborators (2013) argue that "color can be considered as the most expressive medium" (p. 217) of cartographic representations, however, due to established conventions in the use of color scales, sufficient hue and saturation needs to be selected carefully. The authors further suggest to consider the size of map symbols, which also involves the width of linear features, as the second most important graphical variable. According to the researchers, map symbols with larger size and more intensive color are easier to identify in a map. Dong and collaborators (2012) further found that a variable size of linear features outperformed the use of color when communicating traffic maps.

Kubíček and collaborators (2017) conducted a user study to test the applicability of different visual variables for symbolizing linear features in a traffic map. In particular, tasks involved decoding of a single graphical variable or two variables simultaneously, while response times and error rates in map-reading tasks were measured. The authors found that the variables *color hue* and *size* are more efficient in communicating information than *shape* and *color value*. Regarding the width (size) of a road segment, the authors further propose that a road, which is represented as wider on the map, might be assumed to have a larger road capacity in the actual road network. However, it could also represent a larger number of cars driving along the road (higher traffic volume). Successful decoding of such a visual metaphor is assumed essential for most effectively communicating traffic-related route information. Goldsberry (2008) further investigated, if the use of different visual variables for symbolizing map objects affects the perception of traffic maps. Despite violating conventional cartographic visualization rules, the author proposed an approach for using cultural metaphors like traffic lights, for enhancing the intuitiveness of the map representation. Results from this study indicate that the map-readers seemed to easily decode the meaning of the information associated with the symbolization, despite the absence of a legend. For visually representing speed and depicting movement dynamics using line features, Lautenschütz (2012) proposed different potential visualizations, such as dot representations using variations in line spacing, line thickness, and color hue as perceptually salient features. The author concluded, "that the dispersion of points along the line and the shape of the representation influence [a map viewer's interpretation of the presented] objects and their behaviour" (p. 347). Stachoň and collaborators (2013) suggest that different types of map symbols have a different impact on the map-reader's ability to decode the communicated information. Furthermore, in a map reading task, differences in speed and interpretation correctness are expected between map-readers, depending on the level of experience in map use.

3.2 Cartographic generalization for route map communication

In addition to using graphical variables for symbolizing favorability of route options, researchers further considered using cartographic generalization techniques for improving map usability and communicating route information.

Findings from research in cognitive psychology indicate that people focus on individually perceived relevant information when communicating route information to others, while cognitively abstracting the geographic space. Commonly observable characteristics of these *cognitive maps* (Tolman, 1948; Tversky, 1992) relate to cartographic generalization techniques, such as *selection, distortion*, or *simplification* (Agrawala & Stolte, 2001; Downs & Stea, 1973). These characteristics imply that the perceived representation of the route may differ substantially from the actual shape (Skubic et al., 2004). But since for route choice, knowledge about the exact geometry of a road is not suggested to be essential, an intuitive representation based on abstractions commonly applied in hand-drawn route maps is proposed to enhance overall route map usability (Agrawala & Stolte, 2001).

In practice, geometric abstractions like the distortion of metric distances (Magel & Sadalla, 1980) are commonly applied in schematic maps such as metro maps to simplify the understanding of complex network structures and to facilitate route planning (Avelar & Hurni, 2006; Roberts et al., 2013). In the context of a road network, Golledge and Zannaras (1973) discuss that the actual travel time has a direct influence on the perceived traveled distance. In particular, this is suggested to be affected by the traffic dynamics (MacEachren, 1980; Saedi & Khademi, 2019). These findings indicate that preserving metric distances is not essential when visually communicating route information (Tversky & Lee, 1999).

While most of the research work concerning the use of cartographic generalization techniques for improving map usability focuses on map types such as thematic maps or road maps that do not focus on a specific region within the map (Buttenfield & McMaster, 1991; MacEachren, 1995), few researchers investigated possibilities for specifically improving usability of route maps. For effectively communicating a specific route, Agrawala and Stolte (2001) developed a tool for automatically generating route maps based on different cartographic generalization techniques. The generalizations applied in their route maps are based on cognitive psychology research related to schematizations frequently applied in hand drawn maps. The idea of this approach is motivated by the assumption that standard computer-generated route maps are often difficult to use, because due to the constant scale factor, these maps are cluttered with detail information, which is not relevant for the map purpose. This, however, causes short roads or other small map objects that might be important for the user, to be hardly visible. Therefore, it is proposed that generalizations commonly applied in hand drawn maps might be more effective for route choice and navigation purposes than conventional route map designs.

The route map generalizations applied by Agrawala and Stolte (2001) aim to produce maps that emphasize and clearly visualize the most essential information for following the route. While focusing on clearly presenting all turning points along the route (Denis, 1997), the used generalization techniques involve the distortion of road length and angles and a simplification of the road shape for emphasizing the most important information. Distortion of road length is primarily applied for exaggerating the length of short roads to ensure their visibility. Turning angles are mostly adapted (e.g. to right angles) to form a cleaner looking map (Tversky, 1981), based on the assumption that knowing the turn direction (but not the exact turning angle) is sufficient. Shape generalization is achieved by simplifying the road shape, which for example involves drawing line objects as straight lines instead of illustrating their real shape. Hence, individual route segments are easier to be differentiated as separate entities and emphasis is placed on clearly visualizing characteristics of objects that are relevant for the navigation task, such as decision making points. In addition to these geometric modifications, the resulting maps include further context information such as important crossing streets and local landmarks, which are suggested to be helpful for navigation. The potential of route shape simplification for influencing pedestrians' route choice is further investigated in a more recent study conducted by Ti and collaborators (2023). While shape simplification has generally been found effective for influencing route choice, they found that this influence reduces, in case a recommended route is considerably longer than the shortest or fastest route.

Agrawala and Stolte (2001) suggest that applying generalization techniques to a route map can cause confusion or mislead the map-user, if distortions are carried to an extreme, while map usability can be highly improved, if the map modifications are performed carefully. Hence, it seems that for a route map to be effective, the map needs to be prepared using an appropriate level of modification.

While the approach followed by Agrawala and Stolte (2001) focuses on the geometric modification of routes as a sequence of road segments, further research has been conducted concerning the geometric distortion and displacement of objects in the entire map space, including optimization of road network structures, in order to enhance legibility and usability of road maps for tasks such as wayfinding. In this context, a further method for geometrically distorting the map content are variable scale maps (Harrie et al., 2002), which use mapping functions to present multiple scales in one map for representing an area of interest (e.g. the user's position) in more detail. The distortions in a variable scale map are often produced with a certain function that maps each objects original position to its position in the variable-scale map. This mapping is usually applied in a way that a fish-eye view is simulated. For producing such a view, normally, a large scale factor is defined for a focus point or region, while outside the focus, the displacement of points depends on the mapping function applied. The additional map space that is required by the enlarged focus region is compensated by distorting other parts of the map (Haunert & Sering, 2011). In literature, two different types of mapping functions are distinguished: First, mapping functions that distort the whole map outside the focus, and second, mapping functions that only distort a certain region around the focus. Regarding the second type of mapping function, a variable scale map can be structured in three different parts: An undistorted region of larger scale (*focus region*), a distorted region that surrounds the focus (referred to as *glue* by Yamamoto and collaborators (2009)) and a *context region* that does not belong to the *focus region* or the *glue region*. In the glue region, points are moved a certain distance away from the focus region, resulting from a Bezier interpolation function, while in the context region, the map is kept unchanged.

Based on the concept of a variable scale map, Haunert and Sering (2011) adapted the idea of a focus region for specifically rendering road networks with user-defined focus regions. In their approach, a focus region (for example a very dense road network) and a zoom factor are selected by the map user. As a result, the region of interest is scaled up, providing a clearer visibility of the geographic objects within this area, while ensuring that the map still fits into its original frame. To achieve this, some parts of the map that are not in the focus, are scaled down, which leads to map distortions. However, compared to other methods that use the fish-eye technique, distortions at road segments are minimized.

The definition of multiple focus regions is possible by using polyfocal mapping functions that apply polyfocal projections (Kadmon & Shlomi, 1978). Multiple focus regions become necessary, in case the visibility or the presence of several different areas on a map should be enhanced to emphasize importance of the different focus regions over the surrounding areas in the map.

The previously described different approaches for improving road map or route map usability agree on one important aspect in map design: They suggest that while maintaining geometrical correctness of the road information is less important for the task to be performed by the map user, it is more crucial that all relevant roads and turning points are depicted in the map, with correct topological relations between them.

3.3 Map-based visualization of environmental hazards

Previous research regarding routing solutions that take information on environmental hazards into account, address various different scenarios. For instance, Kalantari and collaborators (2014) used statistical modeling for flood hazard prediction along roads and localized road regions that are suggested to be avoided during rain time. Inanloo and Tansel (2016) proposed an analysis of road networks according to their serviceability for hazardous material shipments. The routing options, in their research, were calculated by accounting for health risks, delay costs, trucking expenses, and proximity to vulnerable areas instead of widely used travel costs based on road length assessment. Similarly, Bęczkowska (2019) introduced a method of optimal route selection for transport of dangerous goods, based on accident probability computation. Among others, hazards such as areal contamination or pollution can serve as an additional scenario for an optimized routing that takes environmental factors into account.

Compared to other types of environmental hazards, air pollution is a widespread problem in the globalized world. Still, travelers are often reluctant to choose a more environmentally friendly alternative over their individually preferred route. In recent years, the issue of intensive air pollution in urban areas has increasingly become a topic of political discussions. In addition to a potential reduction in quality of life in general, there is growing concern about the risk to public health. Of particular interest are measures that intend to prevent exceedance of critical limits for environmental pollutants (e.g. particulate matter concentrations). Besides a variety of other factors (e.g. population growth, development of industry), road traffic is a key contributor to the development of particulate matter concentrations. Thus, high traffic volumes in areas with already increased air pollution can lead to a worsening of the situation (Pant & Harrison, 2013). Various countries have tried to counteract this development using proactive measures – with varying degree of success. Examples are introducing speed limits, low emission zones, toll systems, or aiming at a general reduction in road traffic by imposing driving bans (Holman et al., 2015). Additionally, the concept of sustainable mobility, which is becoming increasingly important in transportation planning, intends to promote eco-friendly, active transport alternatives such as cycling, walking, or using public transport.

For reducing the contribution of motorized traffic to pollution levels, various solutions have been developed as part of industrial projects, including collaborative routing approaches that intend to achieve a better traffic flow and thus save emissions by spending less time in traffic jams (Graphmasters, 2020). Alternative approaches aim at avoiding entire regions of increased air pollution by guiding road users to routes that traverse less polluted areas (Ramos et al., 2018; Mahajan et al., 2019). These approaches could particularly contribute to improve air quality at locations with already increased pollution levels; however, the traveler is not given a choice of which route to take. In addition, sensor platforms nowadays offer the possibility to monitor, visualize and evaluate the development of air quality (Marjovi et al., 2015), as well as allow citizens to participate in these projects themselves.

While calculating optimal routes for reducing overall pollution based on sensor networks is not a new concept (Ramos et al., 2018), previous research in this area has widely omitted the challenge posed by visually recommending a *social route* (Fuest et al., 2021).

Nowadays, many of the route decisions made by travelers are based on cartographic maps as provided by real-time routing applications. Therefore, a clear and intuitive visualization for communicating the mapped information is crucial (Otto et al., 2011). While the inclusion of traffic information in route map visualizations is a very common feature in routing applications or navigation systems, less effort has been done so far when it comes to the visual representation of environmental hazards such as air pollution. A review of previous research on map-based air pollution visualization reveals that a few different types of representations are proposed, among which the use of variations in color for symbolizing the areal distribution of pollution, is most common (Bachtiar et al., 2015; Hasenfratz et al., 2015; Taylor et al., 2016; Engeset et al., 2022). For instance, Boy and collaborators (2015) define a smoke metaphor that visualizes pollution based on variations in grayscale and with varying opacity. Other frequently applied techniques are the use of patterns (Engeset et al., 2022) or contour lines (Clive at al., 2021) for emphasizing the pollution distribution or using a grid for assigning pollution levels for each cell (Timmons & Lunn, 2023). In addition to these areal types of representations, researchers used line type representations, such as using variations in coloring of road segments to represent the degree of pollution (Chen et al., 2022; Garzon et al., 2022). Nurgazy and collaborators (2019) further created an application that provides personalized pollution maps based on the users' pollutant sensitivity levels and color vision impairments.

3.4 The role of emotions in map-based communication

Like any other type of visual representation, map symbols can evoke different emotional responses in the viewer (Caquard & Griffin, 2018). Therefore, it is important to investigate to which extent emotions may contribute to route choice decision making.

Research on emotions related to driving behavior has shown that aggressive driving behavior can be influenced by strong emotions felt by the driver, while *anxiety* and *contempt* showed the same negative and dangerous driving pattern as *anger* (Roidl et al., 2014). Jing and collaborators (2018) further suggest that the feeling of *regret* (or not wanting to experience regret) may contribute to evoking a behavior change. Previous research has shown that it is important to address people's emotions (Roeser, 2012) for understanding the moral impact of the risks related to environmental phenomena. The challenge here is to use map symbols in a way that the symbolization adequately communicates the emotions that are expected to be associated with the communicated scenario. Hence, emotions are suggested to be essential for making rational decisions (Lakoff, 2010). Providing intuitive visualizations that evoke anticipated emotions is expected to make the experience of the mapped phenomena more tangible to the map-reader.

For effectively communicating environmental information, a suitable framing needs to be applied, since the way how information is framed influences how people think about a problem, make decisions and take actions (Scheufele & Iyengar, 2012). Some researchers have attempted to transfer the concept of framing to cartographic language. For instance, Pearce (2008) translated written descriptions of space into visual characteristics using cartographic symbols. For mapping the space according to individual experience, it is suggested to replace cartographic conventions with other expressive forms that directly capture the emotions associated with a place but that may not preserve geometrical correctness. The author used variations in color hue to visually encode emotions such as the perception of danger. Color is commonly used as a variable for expressing emotions, since different colors are associated with certain sentiments or emotions (Kushkin, 2022). However, research has shown that one single color can evoke a wide range of emotions. *Red* color can for example be associated with a very diverse set of emotions including *love*, *anger*, *excitement*, *danger* or *aggression*. Similarly, the color *blue* can be related to very different associations such as *comfort, pleasure, sadness, calmness, optimism, coldness* or *trust* (Demir, 2020).

The decoding of color schemes further depends highly on cultural color conventions and also on the context in which the color is used (Elliot & Maier, 2012). According to Kelly (2019) and Anderson and Robinson (2021), darker color values may be used for showing fear, danger, or sadness of the communicated information, while bright colors may relate to happier situations. Besides the use of colors, visual cues such as shapes or lines are also frequently used in arts for expressing emotions and thus influencing the sentiment of the observer. While round shapes and soft lines and colors usually intend to evoke peaceful, positive feelings, jagged, sharp lines or shapes are commonly used for communicating negative feelings or energy.

Alternative approaches for mapping emotions apply visual variables other than color, such as contour lines or spike shapes for symbolizing the level of emotional arousal (Nold, 2009). Klettner (2019) evaluated the effects of different map symbol shapes on emotional responses by defining bipolar items for emotions based on the *circumplex model of affect*. Accordingly, asymmetric shapes lead to strong and highly negative emotions, while symmetric shapes evoke mild and primarily positive emotional responses. Another study conducted by Carroll and collaborators (2020) investigates the effectiveness of different visual variables to trigger feelings of uncertainty, with the aim to emotionally influence map readers in their path choice. The recommended 'optimal route' was mostly the shortest or fastest route as provided by a routing service. For allowing more intuitive decisions, they used different cartographic design principles, such as *color*, *noise*, *blur*, *sketchiness*, and *scribble*. The study has shown that while map-readers focus on the shortest route as an optimal path, they were also sensitive to the used symbolization, when making a route choice decision. The authors report that wider lines and brighter colors evoked a feeling of faster movement, while a solid line evoked a feeling of safety, and adding scribble to the map was associated with a higher level of stress. Among others, they found that scribble, blur, and noise were particularly effective for communicating the optimal path. Regarding line size, however, Kelly (2019) found that wider lines in combination with darker color value were associated with fear and dangerous situations, which confirms that the interpretation of line size as a visual variable is to some extent ambiguous and highly context-specific (Fuest et al., 2021). Pirani and collaborators (2020) further found that although choropleth maps are easy to use and familiar to many users, they were not effective for evoking emotions, since they have been evaluated as *boring*, *neutral*, or *traditional*. Instead, unusual map types using conspicuous pictographs or symbols that depict the seriousness of a situation were found effective for evoking emotional responses. The authors pointed out that design choices can influence emotions, but they may be incongruent with the topic or data represented (Anderson & Robinson, 2021). Therefore, it is important to relate the mapped emotions to the topic that should be communicated.

For mapping emotions related to an environmental phenomenon, Pearce (2008) suggested applying symbolization not only to a travelled path, but also to the surrounding area for adequately mapping emotions experienced in a situation. Examples for symbolizing areal information are variations in color applied to a choropleth or isoline map (Słomska-Przech & Gołębiowska, 2021).

Further methods applied for encoding perception of the environment are adding text descriptions by labeling a conventional map or visual representations inspired by sketching (Pearce, 2008). In addition to using textual descriptions and visual cues, there are further ways of communicating emotions such as sonification, by transforming data into acoustic signals (Edsall, 2010). Hence, sounds and music may be added to textual or visual representations for creating a more realistic experience of the communicated situation and possibly evoking more intense emotions.

Previous research suggests that for successfully evoking an emotional response, the used symbolization needs to be congruent with the characteristics of the communicated phenomenon. Additionally, a higher level of experienced arousal is suggested to lead to a higher level of motivation, and increase the likelihood of a behavior change (Roeser, 2012).

3.5 Research gap addressed in this thesis

As the literature review on route map visualization has shown, the majority of current routing services produce route maps that primarily recommend time-efficient routes to the traveler, while the visualization of route recommendations is mostly limited to the use of different colors for the route options to facilitate distinguishing them. However, we have also seen that researchers and developers made some efforts to calculate and recommend more social route options that intend to achieve a societal benefit by taking environmental factors into account. However, similar to conventional route or traffic maps, the applied visual representation of these maps intends to inform the map user about different route options, rather than communicating their favorability regarding an environmental issue. Previous research indicates that it is possible to evoke a behavior change in route choice, however travelers seem less willing to change their behavior in favor of a social benefit, if this requires individual effort or potentially leads to individual disadvantages. In this context, previous research has shown that it is important to appeal to people's emotions (Roeser, 2012) in order to present the communicated topic as an emotionally closer issue (Spence & Pidgeon, 2010) and for the traveler to understand the moral implications of risks associated with environmental phenomena.

The literature review has further shown that there are several approaches for improving route map usability, as well as studies that investigate the applicability and effectiveness of cartographic symbolization for influencing route choice. While these approaches to some extent apply nudging techniques for influencing the viewer’s perception of a situation, so far, research has widely omitted the challenge of using map symbolization for nudging a traveler to routes that are favorable for the society.

Accordingly, the main contribution of this thesis is not to develop new routing methods or to compete with existing, widely used route map visualization techniques in terms of usability, but to specifically evaluate the applicability of different types of cartographic symbolization for evoking a behavior change in road users for achieving a societal benefit. The applicability of the proposed symbolization variants is carefully tested in a set of user studies.

4 Framework and data preprocessing

This chapter focuses on the description of the overall research framework developed in this thesis, as well as data preprocessing steps that are required for preparing the automatic route visualization procedure. This preprocessing stage also includes the routing procedure for calculating favorable routes.

4.1 Research framework

The main contribution of the research conducted in this thesis involves developing design variants for symbolizing favorability in route maps and testing the appropriateness of these variants in terms of subjective and objective usability. In this section, a research framework is proposed that serves as a basis for the research work that was developed as part of this thesis. Figure 4.1 illustrates the framework including its different components.

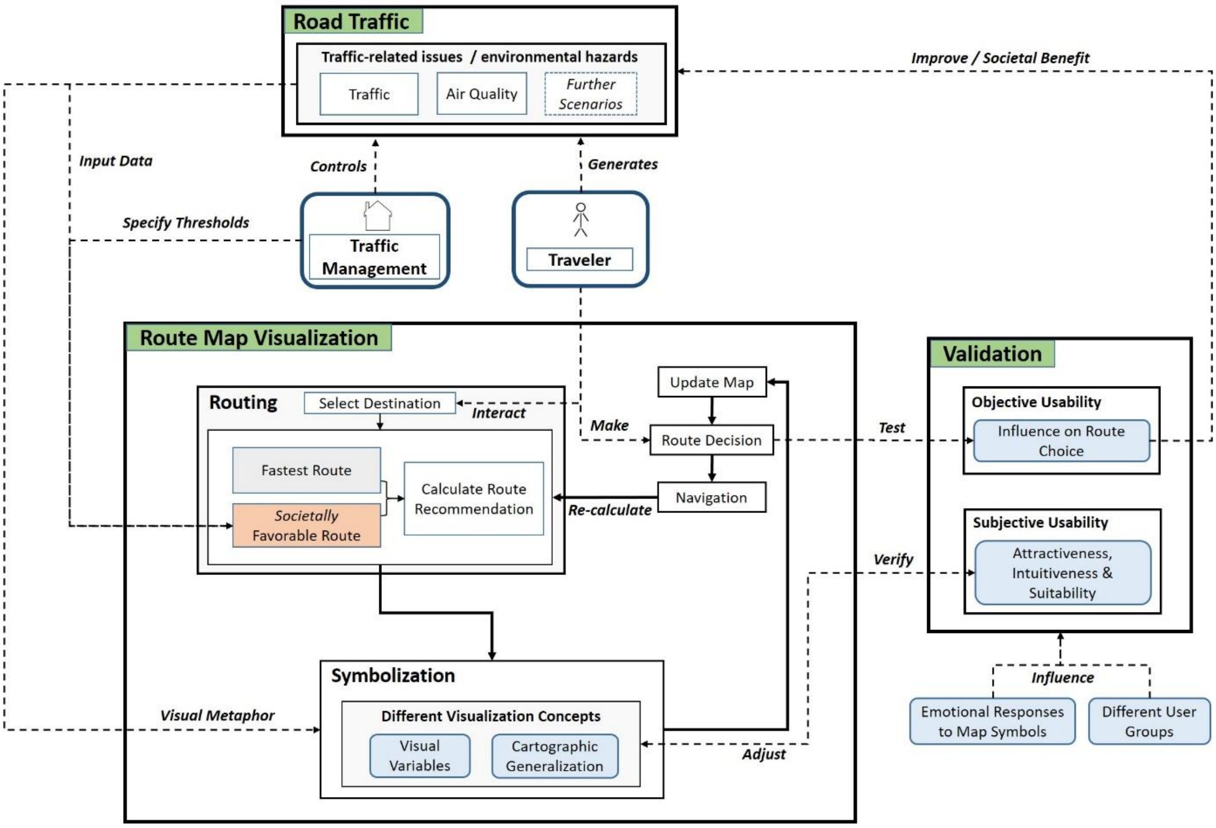


Figure 4.1: Research framework.

The proposed research framework mainly consists of a design component for automatic route map visualization and a validation component for verifying appropriateness of the proposed design variants of route visualizations for communicating *societally favorable* routes.

Different traffic-related issues or environmental hazards could cause various societal challenges that do not only affect the road traffic itself, but also the quality of life of a city's residents. In the further course of the thesis, these societal challenges elicited by traffic-related or environmental phenomena will be referred to as *scenarios*. For each scenario, a normal situation is defined and critical deviations are specified, for which the traffic management intends to take certain measures. Hence, a threshold value is specified that defines a range of *societally favorable* and *non-favorable* measurement values. The measures are all aimed at shifting traffic away from the critical roads concerned, which directly corresponds to the earlier introduced importance of shifting traffic in the context of promoting sustainable forms of mobility.

The route map visualization component consists of a routing part and a symbolization part. It is important to mention that the routing part was not in the focus of this thesis, hence, existing approaches have been used. The routing part is explained in chapter 4.3, while the symbolization part is presented in detail in chapter 5. The procedure described in the route map visualization component refers to the different steps for applying the proposed automatic visualization in a real routing application: After the traveler has selected a target location, in the normal situation, the routing service performs a routing for the fastest (*individually efficient*) route. In case the traffic management recommends that there is for example a need to reduce the air pollution at specific locations, then the routing algorithm is adjusted accordingly using a specific parameter as a weight. In a next step, the calculated route recommendations are extracted and symbolized based on the same parameters. For symbolization, different visualization concepts are used, including visual variables applied to map symbols and cartographic generalization techniques. The resulting route map visualization is presented to the traveler for the purpose of route choice decision making, while the traveler is expected to choose the route that is visually communicated as the favorable route option. Due to the dynamic nature of traffic and different environmental phenomena, during navigation, favorability of route sections might change halfway along the route. This may also require an adaption of the route map visualization. If so, the previously explained route map visualization procedure is repeated before each turn at an intersection.

The validation component represents an important part of the research work conducted in the scope of this thesis, and describes the usability testing regarding the developed visualization methods by performing user studies. Here, both subjective and objective usability is assessed. Regarding subjective usability, attractiveness, intuitiveness and suitability of the design variants for communicating favorability of route options is tested. The responses on subjective usability are used for evaluating, if there is a need for reconsidering the design choices made for symbolization. For objective usability, the focus is on investigating effects of different types of map symbolizations on route choice behavior.

Additional influence factors that are examined as part of the user studies are the influence of different user groups, as well as emotional responses to map symbols. Proposed design variants are suggested being appropriate for visualizing favorability of routes in a routing application, in case both subjective and objective usability testing result in an overall positive evaluation.

4.2 Scenarios

As introduced earlier, the majority of currently available routing services recommends routes that are efficient for the individual traveler in terms of travel time or distance. However, there are cases when it makes more sense to recommend an individually less efficient, potentially longer, but societally more favorable route option to travelers, in order to achieve an overall societal benefit. This could involve resolving or even preventing congestion situations or to prevent the deterioration of environmental hazards such as air pollution, by a better distribution of traffic flows.

Societal challenges that are denoted as *scenarios* in this thesis can relate to a large variety of different traffic-related or environmental phenomena. The methodology developed as part of this thesis is exemplarily applied to two specific scenarios: 1) *traffic* (congestion) and 2) *air quality*. While these two scenarios address important societal challenges that need to be solved for establishing a traveler-oriented traffic system, the methodology can also be adapted to other scenarios.

The geographic extent of a phenomenon related to a scenario can be point-like, linear or areal. Figure 4.2 illustrates schematic sketches in which the observed phenomenon is related to either point, line, discrete area or continuous area geometries.

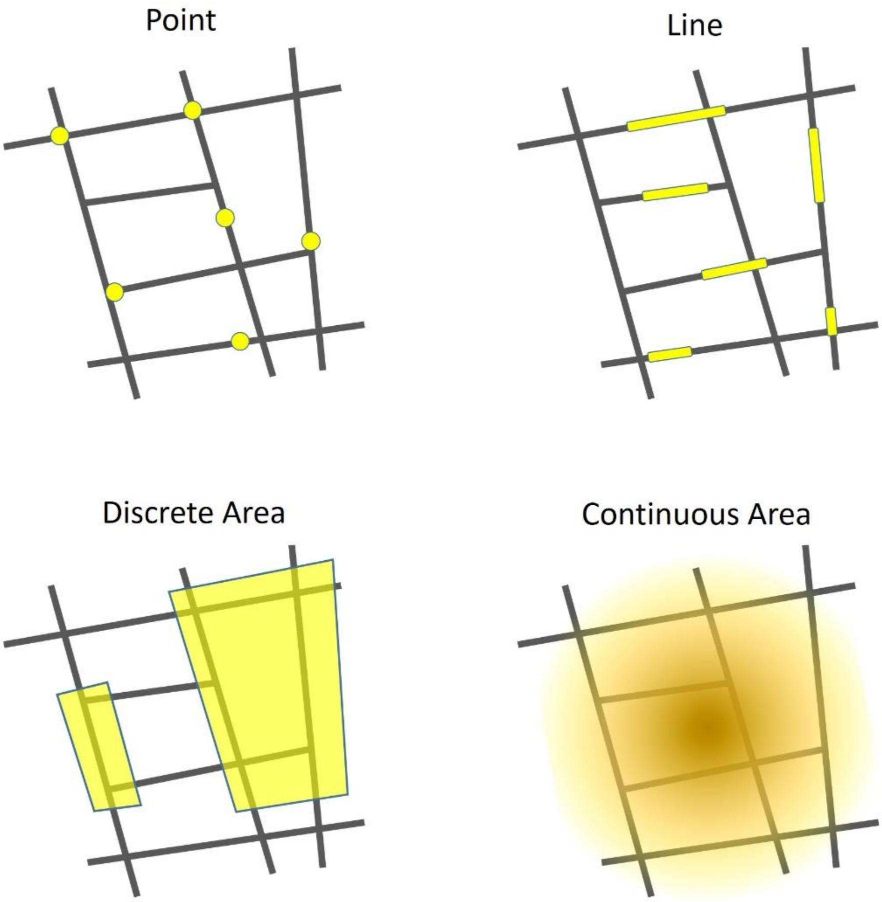


Figure 4.2: Schematic sketches of the spatial extent of phenomena related to point, line and area geometries.

A point-like scenario describes a phenomenon or event that includes data points at one or several different discrete locations distributed across an area of interest. In case of multiple locations, there does not necessarily need to be a direct relation between the events at the different geographic locations. Examples of point-like scenarios are road safety issues, such as locations of increased risk of accidents, which are typically located along one specific road or at intersections. However, the impact of a risk- or accident location does typically not only concern the location itself, but also affects the area directly around it, or along the connected roads. This could for example be in case of a fire that causes smoke in the surrounding area, which potentially leads to such a scenario having rather an areal extent. Also, a suitable weighting of the different locations according to their impact on maintaining a safe traffic system needs to be introduced when calculating and recommending *societally favorable* routes.

A linear scenario describes a phenomenon or event that allows capturing data based on linear features, in particular related to road segments. Apart from the case of traffic congestion or traffic load associated to road segments in general, other scenarios related to linear phenomena are partial flooding of roads due to heavy rainfall or limited accessibility of individual roads due to an event or festival. Similar as for point-like scenarios, weights assigned to line segments can for example provide information on how severe an event is, related to a particular road that is affected.

Finally, an areal scenario describes a phenomenon or event of either a discrete or continuous spatial extent. A discrete areal scenario concerns data associated with one or several regions with a fixed boundary. An example of this type of scenario is the limited access to entire city districts due to an event that affects the whole area. In this case, a specific weight could be assigned to each affected city district, depending on how strongly an area is affected. A continuous areal scenario, on the other hand, is related to phenomena that spread over the geographic space without any sharp boundary. Examples of this type of scenario typically concern environmental phenomena such as different types of air pollution, weather phenomena such as fog, or the spread of viruses or diseases. For this type of phenomena, it is typically not possible to capture data at every single affected location. Since due to the dynamic and continuous nature of such phenomena, and because spatial proximity is expected to result in similar measurement values at neighboring locations (Tobler, 1970), spatial interpolation, for example using inverse distance weighting (IDW), is often performed to estimate data values at all locations across the region of interest. The weighting can then directly correspond to the interpolated values. While for most of these scenarios, the recommendation of temporarily effective routes can lead to individually beneficial routes, not all of these scenarios address social behavior. While influencing the distribution of road *traffic* or *air pollution* can clearly result in a societal benefit, making detours due to events such as heavy rainfalls or fog is not expected to achieve an overall improvement of the situation, but rather a benefit for the individual person that is confronted with the situation. Therefore it is important to point out that while the methodology developed in this thesis can be applied to various (not necessarily *societally relevant*) environmental phenomena, the focus of this work is specifically dedicated to influencing route choice for achieving a societal benefit.

Effective symbolization of a scenario is expected to depend on a suitable choice of map symbols that match the geographic extent of the communicated phenomenon. Hence, effectiveness and suitability of different types of map symbols may vary among different scenarios.

In the following, the characteristics of the two scenarios *traffic* and *air quality* are described in detail.

4.2.1 Traffic

In its usual sense, traffic congestion is considered to be a linear phenomenon, since the geographic extent of the phenomenon is in most cases limited to individual roads within a road network. However, in case an entire region is affected by traffic congestion due to an event, while other regions are not affected, traffic congestion could also be considered as an areal phenomenon. In this thesis, traffic congestion is primarily treated as a linear phenomenon.

Traffic congestion is a widespread problem, particularly in densely populated, urban regions of the world with a large proportion of motorized individual transport. In the usual sense, traffic congestion is characterized by slower travel speeds that result in longer travel times. In case the congestion forces vehicles to fully stop for a period of time, this situation is referred to as *traffic jam*. In many cases, congestion is caused by the road infrastructure not providing enough capacity to cope with the traffic demand. Hence, traffic congestions are often to be expected at peak hours, with a lot of travelers intending to use the same road. Other possible causes of congestions are non-recurring events such as weather events (for example heavy rainfall or snow), road construction works or unexpected traffic incidents such as accidents that require parts of the road to be closed (Afrin & Yodo, 2020). Traffic congestion can further lead to drivers experiencing intense emotions such as anger or frustration (Roidl et al., 2014). While solutions for reducing traffic congestion can for example be related to improving the road infrastructure, increasing capacity of the road infrastructure (*supply*), or reducing traffic load (*demand*), alternative approaches try to avoid congestion before it occurs, by implementing a suitable routing that attempts to assign different routes to travelers with the same destination (Graphmasters, 2020). Further approaches (e.g. *car free cities*) try to implement urban design features to significantly reduce road traffic by motivating travelers to use other, more sustainable modes of transportation such as public transport or cycling (Nieuwenhuijsen & Khreis, 2016). This overall reduction in motorized traffic is furthermore also expected to benefit public health.

In the further course, the traffic congestion scenario is simply referred to as *traffic*. In this thesis, traffic congestion is estimated based on traffic densities measured for individual road segments at a given time. Traffic density k is calculated as the ratio of the number of vehicles n, divided by the length L of a road segment:

$$k = \frac{n}{L} \tag{4.1}$$

For this scenario, it may seem that an *individually efficient* route in terms of travel time would always coincide with a longer, less congested route that is recommended as *societally favorable*. However, importantly, in this scenario, an increased traffic load does not necessarily also result into an overall increased travel time. Hence, a route with higher traffic volume is not necessarily being less time-efficient than a potentially longer, less congested alternative route. Rather, an unusually high traffic volume observed at a specific location is considered as undesirable from a societal perspective due to potential accumulation of pollutant emissions, and the recommendation of alternative routes should improve this situation. Therefore, the threshold between an acceptable and an unacceptable traffic volume may vary depending on the definition of which amount of traffic is acceptable in a specific situation.

4.2.2 Air quality

Different from some other types of environmental hazards, air pollution is a widespread problem in the globalized world. Since air pollution is a source for health effects including multiple life-threatening diseases such as lung cancer, it can be hazardous to each individual person. Hazardous pollutants that are emitted into the air by human activity include among others carbon dioxide (CO_2), sulfur oxides (SO_x), or nitrogen oxides (NO_x), which can cause environmental problems such as the greenhouse effect or acid rain. In the further course of this thesis, the air pollution scenario is referred to as *air quality*.

Among other sources of pollution (including natural sources such as dust, methane or smoke) that may impair air quality in urban environments, motorized traffic contributes significantly to the release of pollutants through exhaust gases or production of particulate matter (PM). According to the World Health Organization (WHO) (2022), particulate matter is estimated to affect more people than any other pollutant. While both PM_{10} and $PM_{2.5}$ can cause health effects in case of a prolonged exposure to highly polluted areas, $PM_{2.5}$ is more likely to severely affect the human body. That is, because due to the smaller size of the particles, chances are increased that they are inhaled into the body.
Table 4.1 provides an overview of the seriousness and possible health effects related to different $PM_{2.5}$ levels. The information is based on the air quality standards published by the U.S. Environmental Protection Agency (2022). Based on this classification, of particular interest are measures like thresholds that intend to prevent exceedance of critical limits for environmental pollutants (e.g. particulate matter concentrations).

Table 4.1: Classification of $PM_{2.5}$ levels and related possible health effects (according to the U.S. Environmental Protection Agency (epa.gov)).

$PM_{2.5}$ (µg/m³)	Air Quality Index	Health Effects (among others)
0 – 12	Good (0 – 50)	Little to no risk.
12.1 – 35.4	Moderate (51 – 100)	Sensitive individuals may experience respiratory symptoms.
35.5 – 55.4	Unhealthy for Sensitive Groups (101 – 150)	Increasing likelihood of respiratory symptoms for sensitive individuals.
55.5 – 150.4	Unhealthy (151 – 200)	Increased respiratory effects in general population.
150.5 – 250.4	Very Unhealthy (201 – 300)	Significant increase in respiratory effects in general population.
250.5 – 500.4	Hazardous (301 – 500)	Serious risk of respiratory effects in general population.

Despite the risk of severe health effects, inhabitants of affected areas are often not or only marginally aware of the risks they are exposed to. Since some of the consequences might not be immediately noticeable to them, inhabitants are often reluctant to change their travel behavior (Evans & Jacobs, 1981). However, the importance of providing environmental information for raising awareness of environmental hazards when making route choice decisions becomes even more apparent, since a recent update of the routing service Google Maps provides the option to visualize map details related to air quality information and wildfires (Google, 2022).

Due to the serious health effects that can occur after prolonged exposure to increased particulate matter emissions, and the possibility to reduce PM concentration by changing driving behavior, in this thesis particulate matter concentration is used exemplarily as a source for air pollution. Similar as other pollutants, particulate matter is a continuous areal phenomenon. Hence, for estimating the impact of particulate matter on route favorability, individual measurement values, captured at different locations spread over an area of interest, are interpolated and then assigned to road segments.

To some extent, the geographical locations of areas affected by traffic congestion and air pollution may overlap, since increased air pollution is often observed in areas with a high traffic load. Still, both scenarios are considered separately, also because the willingness to adapt route choice is expected to vary among these scenarios. It is important to note that for both scenarios, the methodology proposed in this research does not attempt to reduce overall traffic congestion or air pollution, but to achieve a more even distribution of traffic, in order to contribute to a relief of heavily affected roads or areas.

4.3 Routing

This sub-chapter describes the methodology applied for performing the routing procedure. Two types of routings are applied: A fastest route that takes travel time into account, and a *societally favorable* route that takes environmental conditions into account.

4.3.1 Data basis for route calculation

In this work, the road network data required for routing is derived from the *OpenStreetMap (OSM)* database (OpenStreetMap, 2023). OSM is an open source project that has been founded in 2004, with the aim to make large-scale geo data available to the general public. Until then, digital geo data as provided by other sources was usually not freely accessible. OSM allows any user to access, collect and edit geo data, since the data is under a free license. As of now, the geographic data is mapped almost comprehensive, particularly in urban areas. While road network data in general is well covered, other spatial objects like cycling facilities are mapped less complete and in less detail. Since the OSM project allows the data to be edited by all users, the possibility of errors in the data due to incorrect editing cannot be excluded.

In the OSM database, all spatial objects (map features) are assigned so called *tags*. A tag describes the characteristics or attributes of a spatial object, while each object could be described by an unlimited number of attributes. Principal tags for a road network are identified by the key *highway*, which assigns a road class to a road object, and thus helps to indicate the importance of a road object within the road network. Possible tags to assign to an ordinary road object are (in descending order, based on importance): *motorway*, *trunk*, *primary*, *secondary*, *tertiary*, *unclassified* or *residential*. In addition, there exist further possible tags for link roads, special roads types, paths and a variety of other attributes.

In the attribute table of a shapefile, each individual spatial object (e.g. a road segment) in a dataset is described in one specific row. Figure 4.3 shows an excerpt of an attribute table from a shapefile based on road data from *OpenStreetMap*. Typical attributes are the *osm_id*, feature class (*fclass*) or the maximum allowed speed on a road (*maxspeed*). The mentioned attributes are OSM-specific and (in case the data is from an external source) may differ depending on the data source. Importantly, it is possible to add further attribute columns or calculate new attributes, for example the length of a line segment (in this example the distance in meters is named *length*), which might be relevant for further calculation when modifying the data. Furthermore, information on the weighting of road segments, for example depending on environmental factors, can be added in the attribute table.

	osm_id	code	fclass	name	ref	oneway	maxspeed	layer	bridge	tunnel	length
1	363315160	5.152	cycleway			B	0	0	F	F	118
2	62295241	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	T	F	25
3	62295241	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	T	F	24
4	62295226	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	9
5	62295226	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	5
6	363315160	5.152	cycleway			B	0	0	F	F	37
7	363315160	5.152	cycleway			B	0	0	F	F	17
8	363315160	5.152	cycleway			B	0	0	F	F	7
9	363315160	5.152	cycleway			B	0	0	F	F	9
10	9885013	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	1	T	F	21
11	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	10
12	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	9
13	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	10
14	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	8
15	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	7
16	9885012	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	6
17	505164561	5.114	secondary	Bevenroder Straï¿½e	K 3	B	50	0	F	F	11

Figure 4.3: Example of an attribute table of a shapefile describing a line (road) segment originating from OSM road data.

For the web application as described in chapter 7, the automatic routing procedure involves downloading routable OSM data of a specified area using the OSMnx tool. A more detailed description of the procedure is provided in the respective chapter.

4.3.2 Calculation of favorable routes

This section deals with the description of the routing approach applied for calculating favorable routes – including the calculation of a time-efficient route option and a *societally favorable* route. It is important to mention that the proposed methodology always calculates two different types of routes: 1) The fastest route option that takes travel time as a weight, and 2) a *societally favorable* route that additionally takes environmental conditions into account. Hence, the user can always choose between two different route options instead of one option being prescribed, since according to the concept of nudging, it is important that the freedom of choice is preserved.

For demonstrating how the proposed method works, a use case for calculating favorable routes is presented, exemplarily based on air quality measurements (particulate matter concentrations) in the city of Berlin. For preparing the routing, air pollution measurements as provided by the open sensor data platform *openSenseMap* (Pfeil et al., 2015), are used. The area of interest within the boundaries of Berlin includes 328 measuring stations, while 97 stations provide data on particulate matter (PM_{10} and $PM_{2.5}$) concentrations. For the use case, measurements were retrieved around noon – at a day in November 2020 with increased air pollution values.

During data cleaning, several outliers were detected and removed that may relate to measurement errors – referring to extremely high PM_{10} or $PM_{2.5}$ values. In a next step, particulate matter values from the different measurement locations are interpolated (using inverse distance weighting (IDW)) and the resulting values are automatically assigned to a road graph derived from *OpenStreetMap* (OSM) for the region of interest: For each single road segment (edge delimited by two neighboring nodes in the road graph, with a node degree $\neq$ 2), information on the particulate matter pollution at the particular location is stored.

Figure 4.4 shows a map of the test area within the city of Berlin, Germany – visualizing $PM_{2.5}$ concentrations across the city area. A threshold is set at 25 µg/m³, which describes a value that must not be exceeded, in order to reduce environmental damage and health risks for the population. It is clearly visible that while some parts of the city show very low $PM_{2.5}$ pollution close to 0 µg/m³ (green color), large parts of the city exceeded the critical threshold of 25 µg/m³ (orange to red color) on that particular day. Some areas were even affected by extremely high $PM_{2.5}$ values of around 120 µg/m³. Prolonged exposure to these areas may pose an increased health risk.

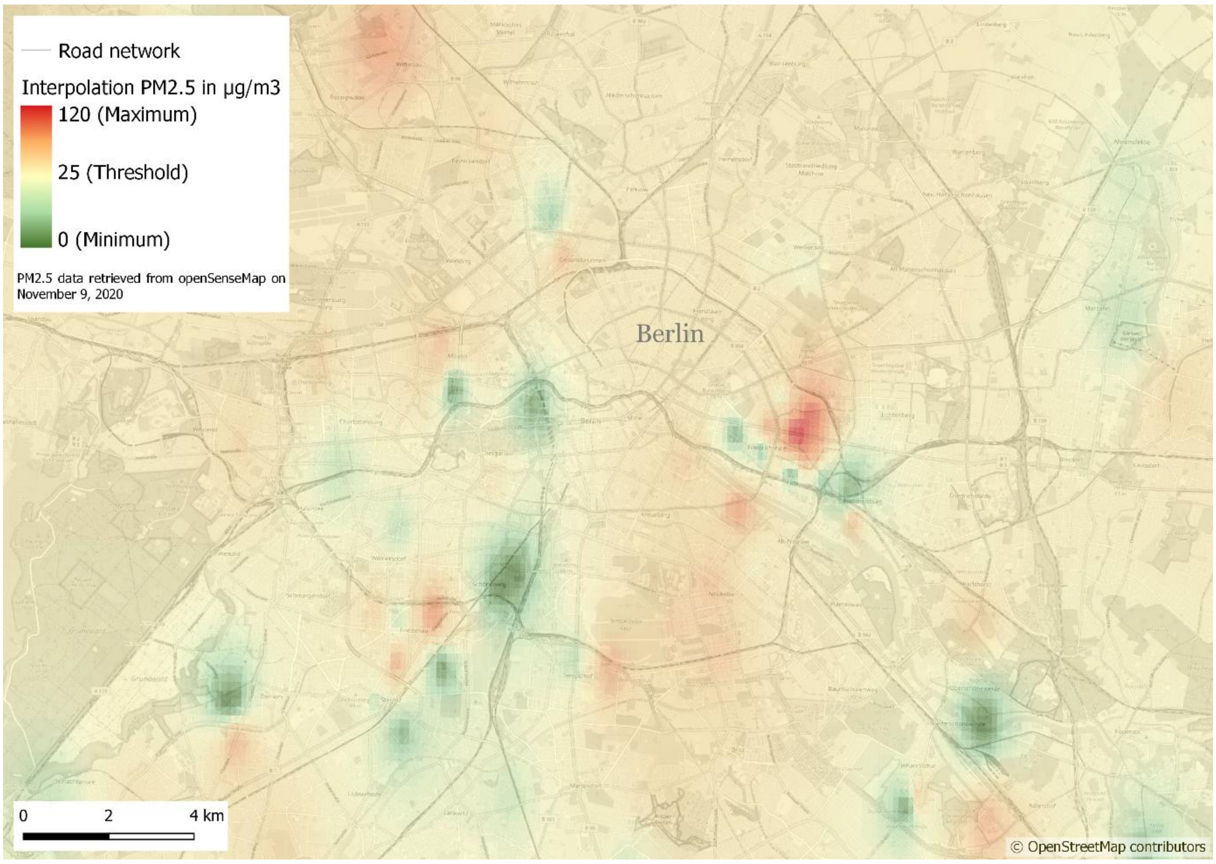


Figure 4.4: Map of the test area in Berlin, showing spatial interpolation of $PM_{2.5}$ values. Map data from OpenStreetMap.

Since the developed system intends to dynamically respond to changes in environmental conditions, the routing service is capable of calculating a most efficient route under regular circumstances (i.e. no external influences), as well as calculating a favorable route when taking traffic-related or environmental information (e.g. air quality levels or traffic density values) into account. While the regular routing produces the fastest route option that may be efficient for the individual traveler, the routing under environmental conditions calculates a *societally favorable* route, for example avoiding further accumulation of particulate matter. For the calculation of the recommended route under regular conditions, the shortest path algorithm is used, while taking travel time as a weight. More specifically, for each road segment, the traveled distance is divided by the maximum speed as provided in the OSM data (*maxspeed* attribute information).

$$weight = \frac{distance}{MaxSpeed} \tag{4.2}$$

Changing the route calculation based on environmental issues is achieved by adjusting the weights on the edges of the graph. The idea is that unfavorable route segments should be avoided, which are therefore penalized with a higher weight. In case for example the air quality is temporarily deteriorated in particular areas, the developed tool allows to control for routes to be recommended by setting a threshold. For different environmental or traffic-related phenomena, this threshold can vary dynamically based on the application, or they can be fixed values as defined by traffic- or environmental authorities, which are legally binding, while an exceeding of the thresholds needs to be avoided. For the case of particulate matter pollution, a threshold of 25 µg/m³ for $PM_{2.5}$ and 50 µg/m³ for PM_{10} is defined, which is based on the threshold set by German law. Measurements that exceed these thresholds are specified as potentially hazardous to health. For contributing to reducing overall pollution of areas with an increased level of particulate matter, route segments that cross these areas are therefore recommended to be avoided. For that purpose, a factor *r* is introduced, which determines if an observed value is located within the acceptable range, or if it exceeds the defined threshold. The value *r* is calculated as the ratio of the *observed value* (measurement) and the *threshold* that has been set.

$$r = \frac{observed\ value}{threshold} \tag{4.3}$$

For the test area, the maximum possible value for *r* is calculated as 120 µg/m³ (*observed value*) divided by 25 µg/m³ (*threshold*), resulting in a value of *r* = 4.8. It is important to mention that the calculation of *r* is not limited to a specific environmental phenomenon, but can be applied using any type of *observed* value as an input, as long as there is a possibility to define a critical *threshold*. In case the observed phenomenon consists of discrete, areal objects with clear boundaries, it is proposed as part of this thesis to adjust the calculation of *r* by calculating the average of all *observed values* within a region, which is then divided by the *threshold* value. These regions can either include only *observed values* below the defined *threshold*, or above the *threshold*.

In case the performed routing takes these environmental conditions into account, the weight calculation from equation Eq. 4.2 differs depending on the value *r*. If a road segment is assigned a value larger than 1 (exceeding the *threshold*), the distance weight is multiplied with *r*. The inclusion of *r* in the calculation causes the edge weight to increase the travel time spent on unfavorable route sections. Due to the resulting large weight, severely affected road segments are likely to be excluded from the calculated route. For both routing variants, the weighted shortest path is calculated as the recommended route option. In this thesis, routing is performed based on Dijkstra's algorithm (Dijkstra, 2022). However, the calculation can be performed with any shortest path program, once with the normal weights (resulting in the shortest paths), and once with the adjusted weights, resulting in optimized paths. As all segments' weights are adjusted based on the underlying phenomenon, several instances of increased values can also be handled. This calculation can further be done dynamically, to adjust for changes in the environment, leading to new recommendations.

4.3.3 Routing results

Figure 4.5 shows an example of how the two different routing variants can result into different route recommendations depending on the defined edge weights. Route option 1 is calculated as a result of the regular routing, while route option 2 is calculated as the *societally favorable* route option (here in this example with respect to $PM_{2.5}$ pollution, hence denoted as *pollution avoiding routing*). While route option 1 is shorter and more direct, is crosses an area of particularly high air pollution. Route option 2 however, is longer and less direct, but tries to avoid crossing the highly polluted area by making a detour. The resulting route guides the road user through less severely polluted areas – with the intention to contribute to a relief of areas that are already highly contaminated. When comparing the weighted distance for the two different route options based on either the regular routing or the pollution avoiding routing, it can be seen that, not surprisingly, in the regular scenario, the weighted distance for the shorter route option 1 is much lower than for route option 2. Considering the pollution avoiding routing, however, the increased values for *r* in the area that is crossed by route option 1, have caused the weighted distance to increase, while recommending the longer route option 2 that avoids the highly polluted area. It should also be noted that the resulting weighted distances could differ considerably between the two routing methods – due to the above-explained differences in calculation methods.

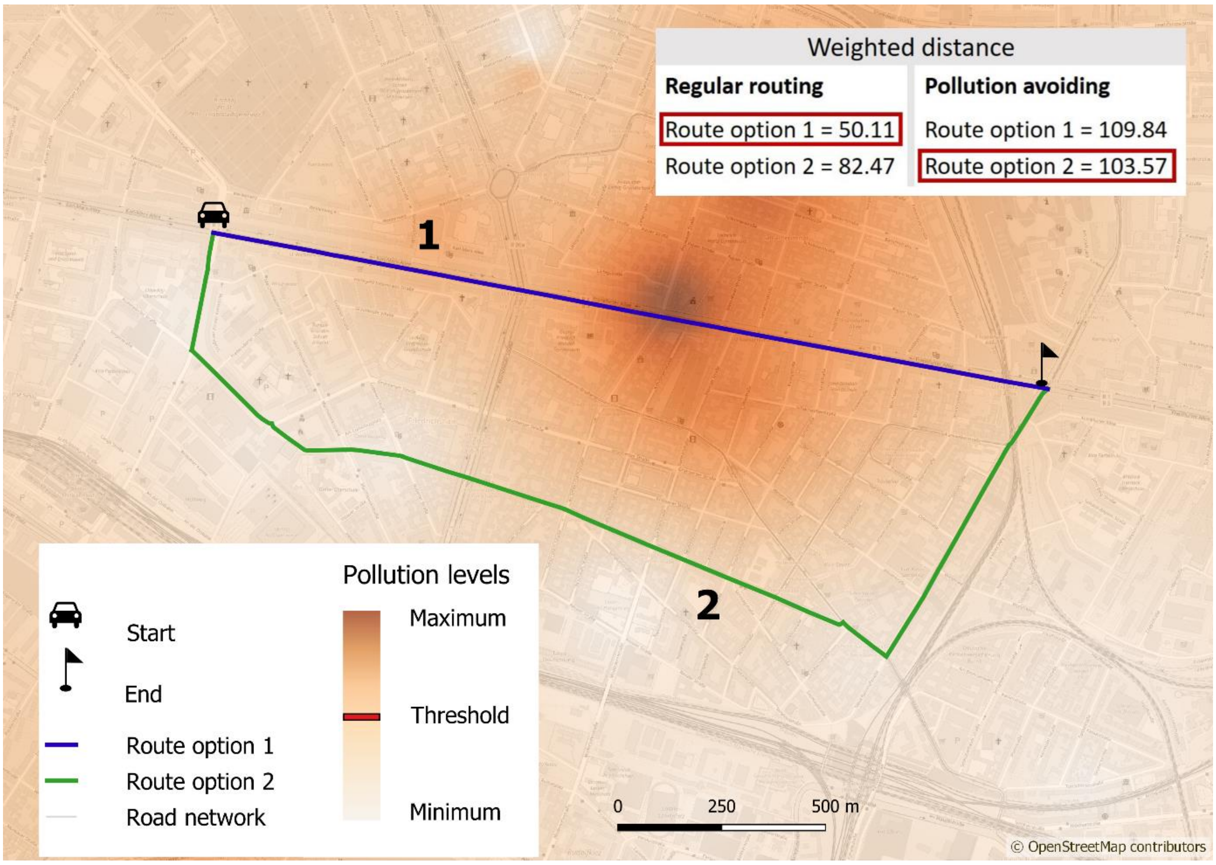


Figure 4.5: Route options as calculated by the regular routing and the pollution avoiding routing based on particulate matter concentration ($PM_{2.5}$). Map data from OpenStreetMap.

The calculation of the proposed routing method that considers traffic- or environmental conditions obviously directly depends on the spatial distribution of the phenomenon. Thus, the route recommendation avoids highly affected roads or areas by preferring the fastest road segments with an observed value below the threshold for making a detour. For estimating the maximum possible length of a detour, the maximum value for factor r needs to be considered. Currently, no upper limit is set, since the raw *observed values* are used for the calculation of r.

To ensure that detours are kept as short as possible, the maximum that an observed value can assume for a particular phenomenon could be defined. This value could result from the outlier removal procedure, while, for definition purposes, the average maximum value of multiple datasets related to the same observed phenomenon could be calculated.

Particularly, in the event of generally low environmental influences on the traffic situation, the two routing methods could result in calculating the same route. In that case, the developed system would recommend and visually communicate (only) the *individually efficient* fast route, which would then also serve as the *societally favorable* route at the same time.

5 Visualization concepts for designing ‘social’ route maps

This chapter presents the main methodological contribution of this thesis related to designing social route maps. Detailed information is provided regarding the different visualization concepts developed for symbolizing favorability in route maps, including the use of visual variations on map symbols and cartographic generalization techniques. Furthermore, different potential design variants of route maps are proposed.

Once possible route options have been calculated based on the different criteria, an appropriate visual communication of the favorability of route options using variations in symbolization, is suggested to be crucial for successfully motivating a traveler to follow a nudge towards choosing a *societally favorable* route.

Figure 5.1 shows possible types of visualizations and geometries that are proposed to be applicable for symbolizing traffic-related issues or environmental phenomena in route maps. Visualization types and geometries that are in the focus of this thesis are marked by a red frame, while types and geometries which are addressed to a lesser extent, are grayed out. The visual modifications applied to route maps can be related to different traffic-related issues or environmental hazards, such as traffic conditions or air pollution. For each of these scenarios, two types of visualization are possible – they can either be *static* or *dynamic*. In both cases, the symbolization can be applied to either point type, line type or area type geometries. In route maps, roads are the most common line type geometry features, while areal geometry features (polygons) can either relate to continuous objects or discrete objects. An example for a continuous (field) object is a layer of emissions that are everywhere and thus is not delimited by clear boundaries. The boundaries of discrete areal objects, however, are clearly defined and could relate to a city district or a temporarily prohibited area. Apart from applying symbolization to either line type or area type geometries, route maps can also combine the symbolization of both geometry types at the same time. This could possibly also relate to combinations involving point geometries.

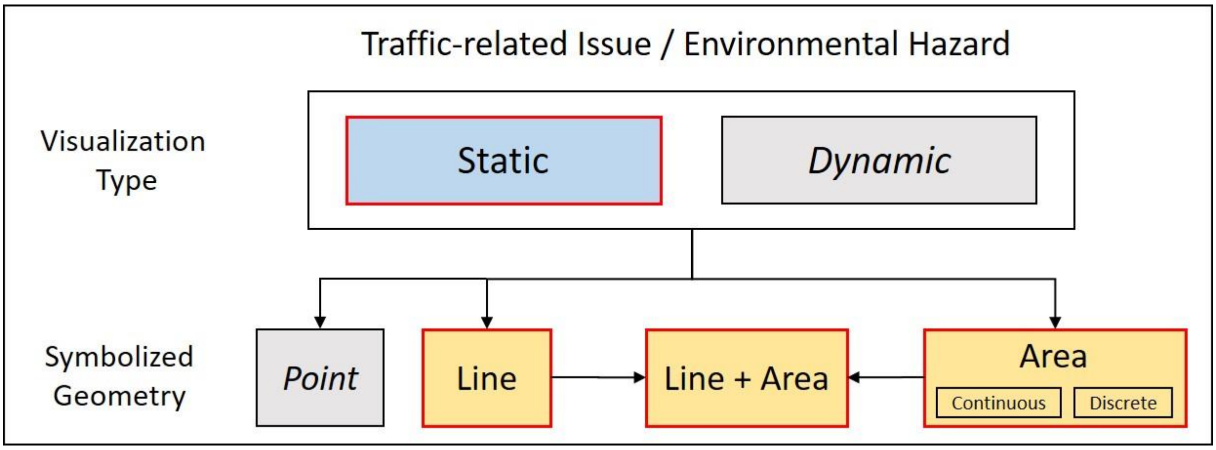


Figure 5.1: Possible types of visualizations and geometries for symbolizing traffic-related issues or environmental phenomena in route maps.

In the further course of this thesis, different design variants for symbolizing favorability of route options are proposed for the different types of geometries. Although point type modifications are also possible to be applied for mapping environmental phenomena (such as symbolizing chimneys as a source for air pollution), they are not the focus of this thesis. That is, because the extent of an environmental phenomenon rarely relates to point-like objects, since even if the source of impact is considered as point-like, usually, parts of the surrounding area or streets are affected as well.

Also, it is important to point out that as part of this thesis, route map visualization is focusing on static representation, since static route map displays are the most commonly used representations in current routing applications for making a route choice decision. Therefore, all described design variants are related to a static type of visualization, unless otherwise specified.

5.1 Map symbols

For visually communicating favorability of routes, the approach proposed in this thesis uses different visual variables (Bertin, 1983) applied to map symbols. The applied visual modifications are related to line objects or areal objects; while the resulting map can either use one of the geometry types or combine both within one map. Furthermore, the applicability of a large variety of different types of symbolization is tested, including established graphical symbols, but also newer experimental approaches, for example using cartographic generalization techniques.

In principle, any map symbol could be eligible for application to visualizing favorability in route maps. That is, because from a methodological point of view, the most important requirement is that the different levels of favorability can be represented by graphical differences defined for a map symbol. Yet, some symbols seem generally more appropriate for application to route maps than others. Additionally, differences in the applicability of map symbols for representing different environmental phenomena can be expected. It is important to mention that in this thesis the focus is on cartographic design tools that are potentially applicable to a large number of different phenomena.

The cartographic design tools described in chapter 2.3.2 consisting of the basic graphical elements *points*, *lines* and *areas*, as well as the composite signs *cartographic symbols*, *diagrams*, *half tone* and *map font* can be combined with the visual variables (see chapter 2.3.1) for representing graphical differences of map objects (Hake et al., 2002). All possible combinations of graphical elements and composite signs with visual variables result in the totality of possible design variants, as illustrated in Figure 5.2.

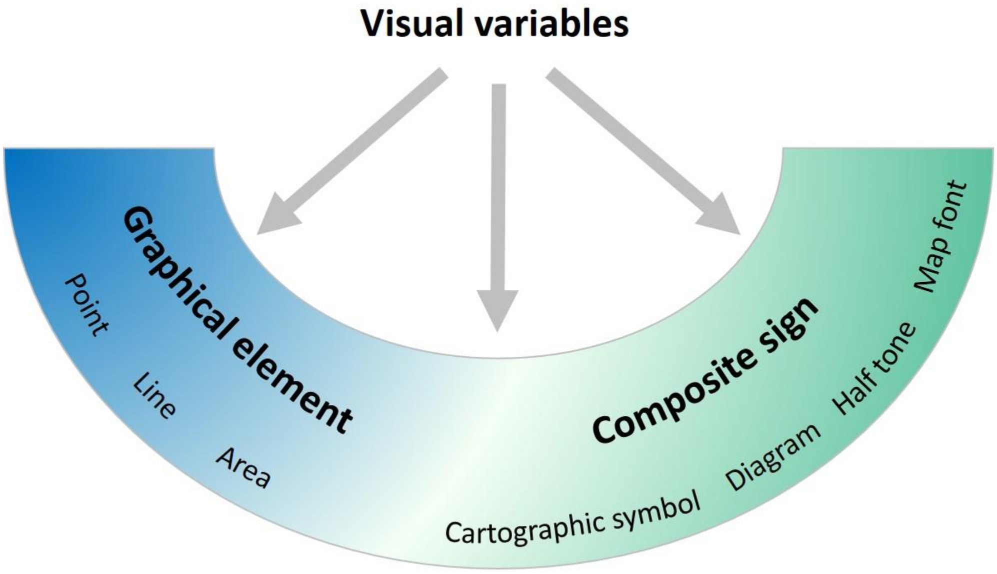


Figure 5.2: Totality of possible design variants as combinations of graphical elements and composite signs with visual variables.

Among the different cartographic design tools, in addition to the graphical element *point*, the composite signs *diagrams* and *map font* are not considered in the scope of this thesis. This is primarily because diagrams and font are both design tools that are most effective for providing additional explanatory information. While an application of these design tools could be possible for communicating favorability in route maps and enhancing their clarity, this thesis was specifically focusing on testing the usefulness of applying visual variations to graphical elements or symbols. Half tone is used marginally in this thesis as part of the *deformation* variant in user study 3 (see chapter 6.3.3), by using shading for symbolizing depth of a region. Particularly map fonts may be used complementary to the used symbolization, for example to strengthen the route recommendation.

Due to the very large number of possible design variants that could result from all possible combinations of graphical elements and composite signs with visual variables, it is clear that not all possible options can be tested for usability in the scope of this thesis. Therefore, in this thesis, a set of variants is tested exemplarily for their effectiveness for influencing route choice. The proposed design variants are suggested to be applicable to the tested scenarios. However, it is important to note that there might be further successful variants, which are not considered in this thesis. The different tested design variants are discussed in detail in the descriptions of the user studies (chapter 6). Map examples of different proposed design variants of route maps can be found in chapter 5.4.1, chapter 6.2.4, and chapter 6.3.3.

In this thesis, the data used for communicating favorable routes (such as traffic or air quality information), mostly relates to numerical levels of measurement, which, as introduced in chapter 2.3.1, indicates that visual variables such as *size* or *location* could be used most effectively. However, for the purpose of nudging map-readers towards more *societally favorable* routes, it is more important to communicate the level of favorability than to present the actual measurement values. Hence, visual variables that are more appropriate for ordinal or nominal levels of measurement could potentially also be used effectively. Therefore, for the methodology developed in this thesis, the choice of visual variables applied to map symbols is not limited to specific levels of measurement, which allows a broader range of possible design variants.

For creating such design variants, it first needs to be defined how the graphical differences in symbolization are calculated and presented. For this, a description of the visual characteristics of map symbols using eight different visual variables is provided exemplarily, and it is proposed how these variables can be used for promoting *societally favorable* routes. The used variables are: *Intensity value, color hue, blur, size, transparency, scribble, geometric distortion* and *pattern* (for example using icons). Due to low appropriateness for communicating ordinal or numerical data, visual variables such as *shape* and *arrangement* are not used.

While the variables *intensity value, color hue, blur, size, pattern* and *transparency* directly refer to either Bertin's 'traditional' *visual variables* or the extended set of visual variables (Morrison 1974; MacEachren, 1995), it is further explored if there is a potential of applying further, experimental variables for communicating route favorability (such as *scribble*, or *geometric distortion*). Although some of the proposed concepts may not be counted as a *visual variable* as such, in this thesis, all applied variables are denoted as *visual variables.*

Some of the used visual variables (such as *transparency* or *blur*) are inspired by previously developed approaches for visualizing uncertainty in maps (Kinkeldey et al., 2014; MacEachren et al., 2005). Kunz and collaborators (2011) apply visual variables such as color hue, saturation and value, as well as transparency, pattern and blurriness for the depiction of uncertainty in natural hazard assessment. MacEachren (1992) further introduces the graphical variable *fog* for representing uncertainty that intends to give the impression of fog passing between the map-reader and the map by varying the transparency of the *fog* layer. Thus, some of the design variants proposed as part of this thesis, such as *transparency* or *pattern* are inspired by the concept of the *fog* graphical variable. Other variants take up alternative ideas for creating intuitive navigation interface designs (such as *scribble* or *pattern* using conspicuous icons) – with the purpose of influencing a user's decision making (Carroll et al., 2020; Pirani et al., 2020). While the majority of these variables are based on variations in symbology, the variable (*geometric) distortion* includes a modification of the original geometry of line segments, and specifically refers to the cartographic generalization technique explained in chapter 5.3.1 of this thesis.

Table 5.1 provides an overview of the applicability of the eight visual variables to linear and continuous, areal phenomena (possible application is marked by a check mark, not possible application by a cross). While for example in case of air pollution, modification of continuous areal objects could relate to a spatial spread of contamination, visual modification applied to linear objects could relate to the level of contamination mapped to individual roads. A combination of modifying both linear and areal objects is expected to produce a stronger effect in visual communication, while combinations need to be selected carefully, in order to avoid an information overload.

Table 5.1: Applicability of visual variables to linear objects and to continuous, areal phenomena (field objects). Note that for discrete areal objects the visual variables for linear objects can also be applied to the boundary.

Visual variable	**Linear objects**	**Continuous areal objects**	**Combination**
Intensity value	✓	✓	✓
Size	✓	✗	✓
Scribble	✓	✗	✓
Distortion	✓	✗	✓
Color hue	✓	✓	✓
Transparency	✓	✓	✓
Blur	✓	✓	✓
Pattern	✓	✓	✓

5.2 Data-based calculation of graphical differences in symbolization

Similar as for the routing part, the calculation of graphical differences in symbolization as part of the route map visualization procedure directly depends on the factor r (see Eq. 4.3). Figure 5.3 illustrates the suggested graphical differences when applying the eight different visual variables to line and (if applicable) areal features with varying values for r as input data. The visual examples primarily show the application of the different visual variables to the basic graphical elements line and area, while *pattern* shows an example of using figurative symbols in a linear and areal arrangement, while exemplarily applying the visual variable transparency to the symbols for showing graphical variations.

For preparing the automated visualization of favorable and non-favorable routes, the values for r are normalized (referred to as n) to a value range of $0 \leqslant n \leqslant 1$, in order to clearly define the visual characteristics for the minimum ($n = 0$) and maximum ($n = 1$) values for the observed data. Additionally, $r = 1$ (which equals the *threshold*) is always set to $n = 0.5$, serving as a neutral basis for the visual characteristics of road segments or areas that are recommended or non-recommended to drive on or to traverse. However, it is important to mention that with this normalization, in case factor r does not increase linearly, $n = 0.5$ does not always coincide with the value that is located in the middle of the value range of r. Therefore, it is possible that the extent of the value range for *non-favorable* is different from that for *favorable*.

The normalization further ensures the generalizability of the method to different types of input data, given that the minimum and maximum values, as well as the threshold for a phenomenon is known.

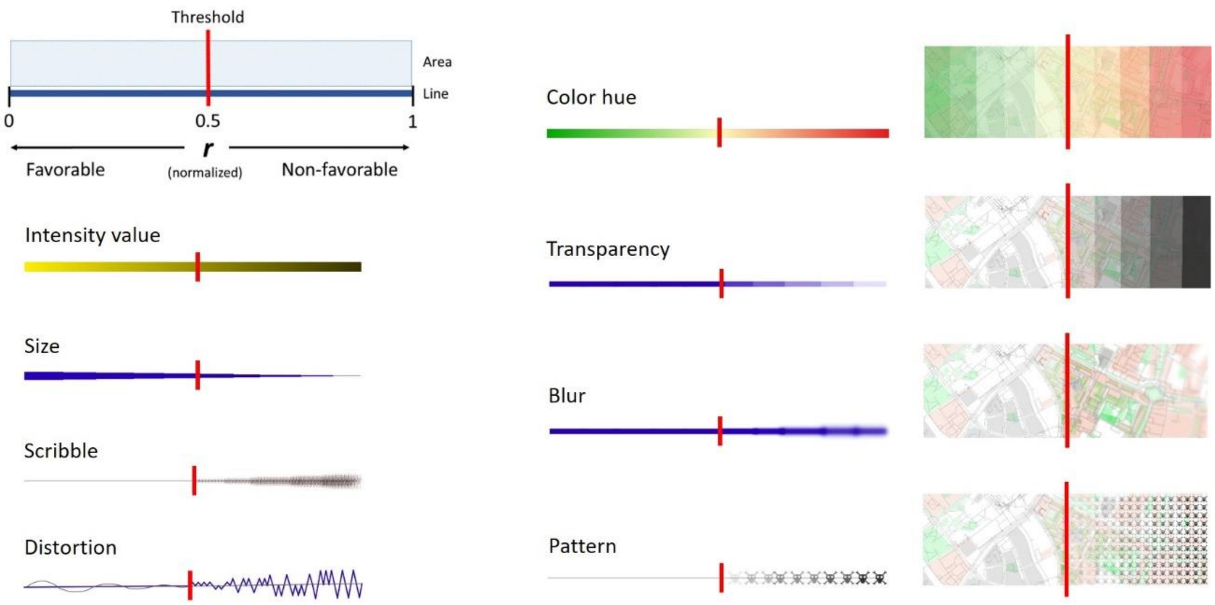


Figure 5.3: Proposed graphical differences for symbolizing favorable and non-favorable areas or parts of the road network (lines) – using the eight visual variables.

For some of the visual variables (*transparency*, *blur*, *pattern* and *scribble*), map objects that are associated with observed values below the threshold are suggested to be not graphically modified, whereas objects related to values that exceed the threshold are always graphically modified with increasing intensity towards visualizing maximum observed values (for all visual variables). Emphasizing the ineffectiveness of areas with increased values serves to point out the deviation of a situation from normal, or desired ("below threshold") conditions. In particular, it is assumed that road users are more likely to change their travel behavior, when negative aspects of the undesirable traffic situation are visually accentuated. With respect to the previously discussed stronger impact on decision making, this principle of *loss framing* is suggested to be more effective for influencing travel behavior than emphasizing positive effects of the desirable traffic situation (*gain framing*) (Spence & Pidgeon, 2010; Scheufele & Iyengar, 2012).

For the visual variables *color hue*, *transparency*, *blur* and *pattern*, graphical differences are defined for both line and areal features. In contrast, the variables *size, scribble* and *distortion* are only used for line modifications, which is due to limited applicability for the purpose of visualizing continuous areal features. In case the addressed phenomenon rather consists of a discrete, areal object (such as the boundaries of a city center), the variables *size*, *scribble* and *distortion* can also be applied to the boundaries of the polygon that describes the discrete object.

It is important to note that the provided design example for the *color hue* variant (ranging from green to red color) does not account for possible visibility issues due to red-green visual impairment. Other colorblind safe gradients may be used to solve this issue, e.g., ranging from red to blue or purple to green (Harrower & Brewer, 2003). For the visual variable *intensity value*, graphical modification of areal features is also possible; however, in Figure 5.3, no visual example of this variable is provided, since it would visually resemble the example for *transparency*.

The graphical differences defined for the design variant *distortion* are based on two different visualization techniques, whose application depends on whether a road is favorable or non-favorable. While visual modification is not applied for a line segment with $n = 0.5$, the degree of distortion (distance of new points added to the line) gradually increases until it reaches its maximum for $n = 1$. Similarly, line segments undergo an increasingly stronger simplification (points removed from the line), with a maximum degree of simplification for $n = 0$. Another interesting pattern is proposed for the visual variable *transparency*, since in this case the effect of the line transparency and the areal transparency is inverted: line modification leads to highly non-favorable segments being represented as more transparent (and therefore hardly visible), while corresponding areal modifications would rather be visualized as more opaque – potentially representing a thick layer of pollution that obscures the underlying road network.

Based on the previously explained graphical differences applied for the eight proposed visual variables, Table 5.2 summarizes the design criteria that are proposed to be chosen for visualizing objects communicated as favorable or non-favorable (representation of minimum and maximum value), by distinguishing between line and continuous area objects. As explained above, for the visual variable *transparency*, the symbolization of favorable and non-favorable parts is reversed when considering line and area objects. Also, for the visual variable *color hue*, a different color range may be used, resulting into different hue for the extreme values.

Table 5.2: Design criteria as proposed for visualizing favorable and non-favorable parts of the environment (minimum and maximum observed values).

Visual variable	Line		Area	
	Favorable	Non-favorable	Favorable	Non-favorable
Intensity value	Light	Dark	Light	Dark
Size	Large	Small	-	-
Scribble	No scribble	High	-	-
Distortion	High (simplification)	High (distortion)	-	-
Color hue	Green	Red	Green	Red
Transparency	Fully opaque	High	Fully transparent	Nearly opaque
Blur	No blurring	High	No blurring	High
Pattern	No pattern	Fully opaque	No pattern	Fully opaque

The visual characteristics of the types of symbolization intend to evoke associations related to the communicated phenomenon. In all cases, the used visual metaphors (Skupin, 2000) intend to communicate areas or roads that are either recommended for travel choices (value *r* below the threshold), or advised to be avoided (value *r* above the threshold) – based on the severity of the observed phenomenon (e.g. pollution level or traffic congestion at the respective locations). For effectively communicating route recommendations using visual variables, it is important that a map-reader successfully decodes the message transferred by a visual metaphor. According to the definition of Peirce (1991) (see chapter 2.3.2), in the *air quality* scenario, most of the used visual variables have the characteristic of a *symbol* that is intended to be interpreted as a layer of emissions showing pollution levels. Accordingly, in the case of traffic congestion, map symbols intend to communicate high or low levels of traffic density by symbolizing viscosity of traffic. Hence, the same type of symbolization may be used for communicating different phenomena, but the visual metaphor associated to a map symbol and suitability of using a symbol for communicating a specific scenario might vary among different scenarios. Furthermore, although many of the widely used visual variables evoke the same associations for many people, e.g. ‘more represents more’ (Roth, 2017), the interpretation of the visual characteristics related to different visual variables is highly context-specific and in some cases not unambiguous. Therefore, the intuitiveness of the symbolization and the suitability of the different visualization methods for visualizing environmental phenomena is evaluated and described in chapter 6.1 of this thesis.

5.3 Visually modified geometry

While the previously described visualization concepts primarily apply graphical variations to map symbols, a further way to communicate favorability in route maps is to use cartographic generalization techniques, such as purposefully distorting the geometry of map objects. In this sub-chapter, three different symbolization variants using cartographic generalization techniques that have been developed as part of this research, are presented. First, a combined algorithm for line distortion and simplification (Fuest & Sester, 2019), second, a method for road length distortion based on a displacement approach, and third, a technique for geometric road network deformation within discrete areas. While the proposed generalization techniques are primarily intended for application to line objects, the last two described techniques may also be used for application to areal phenomena.

5.3.1 Line distortion and simplification

The idea for developing a method that purposefully distorts and simplifies the geometry of a line segment is motivated by previous findings from cognitive psychology research suggesting that schematized maps are easier to process by humans than maps with a high level of detail and that map distortions are a powerful tool for emphasizing important parts of a map and at the same time de-emphasizing less important parts (Avelar & Hurni, 2006; Agrawala & Stolte, 2001).

In particular, previous research suggests that the visualization of a road segment as a straight line may be associated with a very smooth movement in space (Thomson, 2004); and could therefore for example relate to a high traffic flow. In contrast, a less smooth and less trouble-free movement in space may be represented as a more distorted type of line, which deviates more clearly from a straight-line representation. In literature, there are only few approaches, which intend to automatically distort a line (Vinatier & Chauvet, 2017), while the concept of representing a distorted or more simplified shape of a line is suggested to be applicable for symbolizing favorable and non-favorable characteristics related to different types of environmental phenomena.

The developed algorithm combines the geometric distortion (complexification of the line shape) and simplification of line segments in one algorithm (later in this thesis simply referred to as the *distortion* approach), while either applying distortion or simplification, depending on the favorability of the road segment. A line segment to be modified typically represents a real road segment in a road network, but can also relate to other linear structures, such as boundaries of regions.

The decision of whether a line segment is being simplified or distorted (and the corresponding calculation procedure being initialized), depends solely on the previously introduced factor r (see Eq. 4.3). In case of a favorable route segment ($r < 1$), the corresponding line geometry is simplified, while the level of simplification increases with increasing favorability. In contrast, non-favorable route segments ($r > 1$) involve the line geometry being distorted, with increasingly larger distortions for highly non-favorable route segments. In case of a neutral level of favorability (equivalent to the defined *threshold*) assigned to a road segment ($r = 1$), no geometric modification of the line will be applied – and the corresponding line segment will retain its original shape. While in case of line distortion, the number of points constituting a segment increases by adding further points to the line, in case of line simplification, points are removed from the original line segment.

In the following, the two generalization techniques are explained, one after another.

5.3.1.1 Line distortion

Distortion of line segments is achieved by adding further points to a line segment a certain distance away from the line. To further simulate an irregularity of the added distortion, points are inserted randomly, at either the left side of the original line, or the right side.

The distortion procedure works as follows:

Each line segment to be modified involves exactly one starting point $P_a(x_{a,} y_a)$ and one end point $P_b(x_{b,} y_b)$. Starting and end point could for example be defined related to the travel direction of a route, or it can be set arbitrarily, in case no specific direction is involved. For deciding, how many additional points to be created based on each existing line segment, and at which location they should be created, the proposed algorithm involves three different parameters, namely:

np := Number of intermediate points created for each original line segment

fs := Relative distance along a line segment from the starting point of a line segment $P_a(x_a, y_a)$ to base point F

d := Distance perpendicular to line segment from the base point F to the new point $P_n(x_n, y_n)$

Both the number of new points (*np*), as well as the distance to the new point (*d*) can be defined as fixed values. This would mean that for different line segments of a polyline, the same number of new points is inserted or that each new point is placed the same distance away from its corresponding original line segment.

However, for clearly showing differences in the data regarding favorability of road segments, introducing an automatic, data-based calculation of these parameters can be useful. In the following, for both parameters, a data-based calculation is proposed.

The suggested automatic calculation of the number of intermediate points to be inserted for a line segment is based on the *r* value. For this, different levels of intensity of a non-favorable line segment are categorized and assigned as a np value to the input line segment as follows:

$$\forall a \in N$$

$$np = \begin{cases} 0, if\ r \leq 1.0 \\ a, if\ r \in]\, 1.0 + 0.2 \cdot (a-1);\ \ 1.0 + 0.2 \cdot a] \end{cases} \tag{5.1}$$

Consequently, in case a road segment is less favorable, a larger number of new points is inserted.

Figure 5.4 illustrates, how the parameters fs and d are used for determining the location of two new points a certain distance away from the line segment. Point P_{n1} will be inserted on the left side of the line, whereas point P_{n2} will be inserted on the right side.

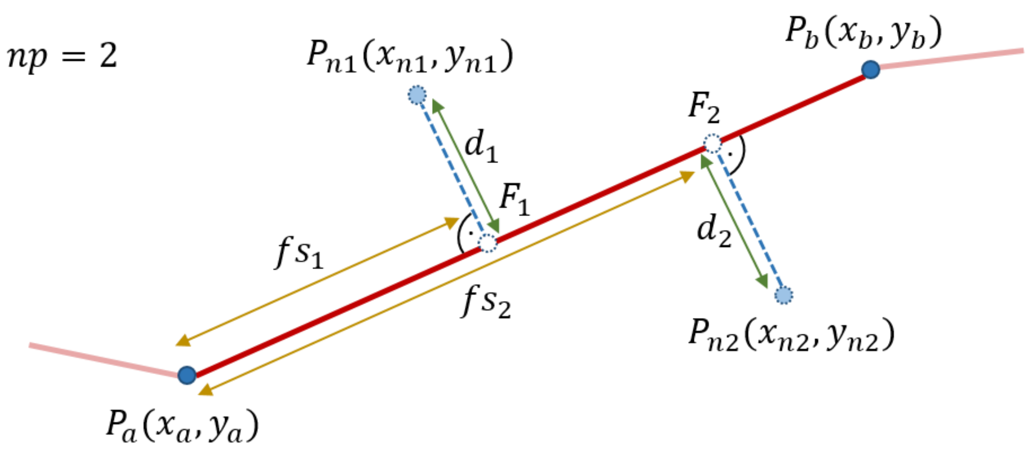


Figure 5.4: Parameters for calculating a new point location.

The parameter fs describes the distance from the starting point $P_a(x_a, y_a)$ of the current line segment to a base point F along the line segment, relative to the total distance between the points P_a and P_b (entire length of line segment). The relative length of fs always depends on the number of points to be inserted. Because for newly inserted, neighboring points, it is intended to keep approximately equal distance intervals along the line segment, normalized sections are created as a proportion of the total distance, with:

$$ds = \frac{1}{np+1} \tag{5.2}$$

For each point i in range $[1, np]$ it is then calculated:

$$fs = ds \cdot i \tag{5.3}$$

Since the newly inserted points do not necessarily need to be distributed using intervals of exactly the same distance, furthermore, a randomization factor is added, which allows slight variations for the calculation of the length of parameter fs. These variations are also shown in an exaggerated form in the schematic illustration in Figure 5.4.

Similar as for the number of points, the data-based calculation of the distance factor (parameter *d*) directly depends on the value *r*. Parameter *d* is defined as follows:

$$d = w * (øLength * r – øLength) \tag{5.4}$$

with *øLength* := Average length among all line segments of a polyline.

For calculation, the average length of all road segments (*øLength*) is used. This means that the distance *d* does not randomly depend on the length of an individual segment, but for all different segments of the input polyline, the value *d* only depends on the value *r* assigned to the road segment. A higher *r* value results in a larger value for *d*, and therefore also causes the new points being inserted further away from the original line.

Importantly, for the calculation of additional points to be inserted, individual line segments (connection between two points) are considered separately. That is, since, different line segments can be assigned different *r* values, the intensity of distortion can differ among different line segments that are part of the same polyline.

The intensity of line distortion can be controlled by adding a weight factor $w > 0$ to the distance calculation *d*. This weighting can either decrease ($w < 1$) or increase ($w > 1$) the distance to the new point. By default, the weight factor is set to $w = 1$. The weight factor is introduced in order to provide the option to manually adapt the intensity of distortion. This could be necessary, in case it is desired to yield a visually more pleasing visualization result, or to avoid the distortion getting too extreme.

Once the parameters fs and d are calculated, the next step is to calculate the point coordinates for determining the location of a new point $P_n(x_n,\ y_n)$. At first, the base point F is calculated as follows:

$$dx = x_b - x_a,\ dy = y_b - y_a \tag{5.5}$$

$$F_x = x_a + fs \cdot dx, F_y = y_a + fs \cdot dy \tag{5.6}$$

Additionally, a randomization is applied, for deciding, if a new point will be inserted at the left side or the right side of the existing line segment. Due to this randomization, at different iterations of the algorithm, the visualization results can differ for the same input line object. The direction perpendicular to the line segment at which the new point will be inserted can be defined by rotating the direction vector – either to the left or to the right – while exchanging the gradients of x and y. Inserting the point on the left side is calculated as:

$$vx = -dy,\ vy = dx \tag{5.7}$$

Accordingly, inserting a point on the right side is calculated as:

$$vx = dy,\ vy = -dx \tag{5.8}$$

The point coordinates for the new point P_n are then determined as follows, with $dist$ denoting the distance along the original line segment:

$$x_n = F_x + \frac{d \cdot vx}{dist},\ y_n = F_y + \frac{d \cdot vy}{dist} \tag{5.9}$$

Figure 5.5 shows four different sample line distortions generated based on the previously presented algorithm, illustrating how the shape of the resulting new line differs when varying the number of newly inserted points (parameter *np*) or the distance to the new point perpendicular to the line (parameter *d*); while inserting new points randomly on either the left side or the right side of the line. In all cases, the dashed red line represents the original line segment, whereas the solid green line illustrates the new polyline. Figure A depicts the case that a relatively small number of additional points is inserted to form the new polyline, combined with a relatively small distance perpendicular to the original line segment. The resulting new line then only slightly deviates from the original line, equivalent to the associated *r* value being only slightly larger than 1. For figure B, the same distance value is calculated, however more points are inserted. Consequently, the resulting line appears as less smooth, since – given the larger amount of points inserted – the angles between two adjacent new line segments get smaller (if points are inserted on different sides of the original line); resulting into a more *zigzag*-like shape. When increasing *d*, this effect is even more noticeable, resulting into very large distortions, which hardly correspond to the shape of the original line any more (particularly visible in figure D). It is important to note that, when executing the algorithm again, the visualization results can be different for the same line segment with the same parameter specifications – due to the introduced randomization factors.

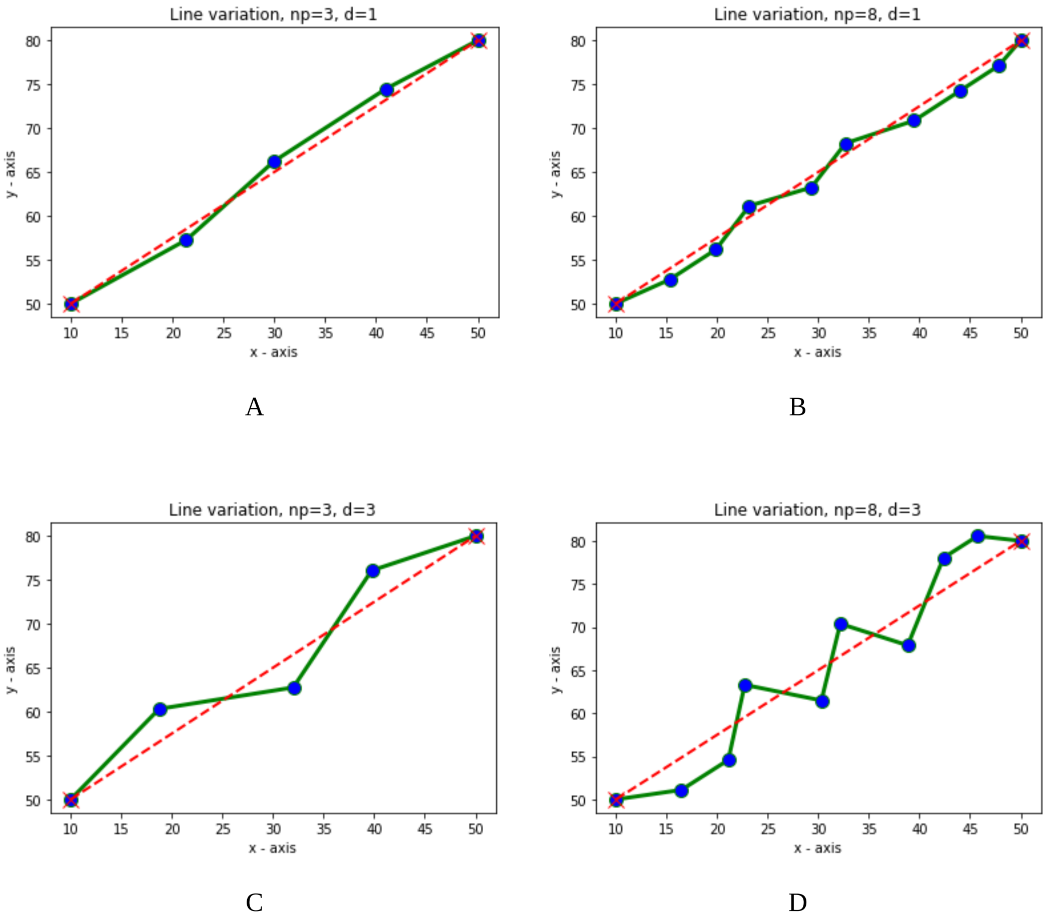


Figure 5.5: Line variations using different values for np and d.

Since in road network shapefiles (such as those provided by OSM), individual line segments of a polyline usually differ in length from other segments of the polyline, adding points to line segments of different length using the above-described procedure may result in a very irregular shape of the distorted line. To make the structure of the distorted line look more regular, and to make the distances between points less dependent on the structure of the data, a division of segments into parts of equal length is introduced. This parameter of segment length (*seg*) for segment division is manually set.

The number of segments *sn*, into which the polyline will be divided, is calculated as follows:

$$sn = \text{round}\left(\frac{dist}{seg}\right) \tag{5.10}$$

The calculation with rounding avoids that after the segmentation, there are no very small line segments left, which could cause a visual effect that is very different from the distortion of the regular sized line segments. Importantly, the segmentation is only applied to polylines with segments of the same *r* value.

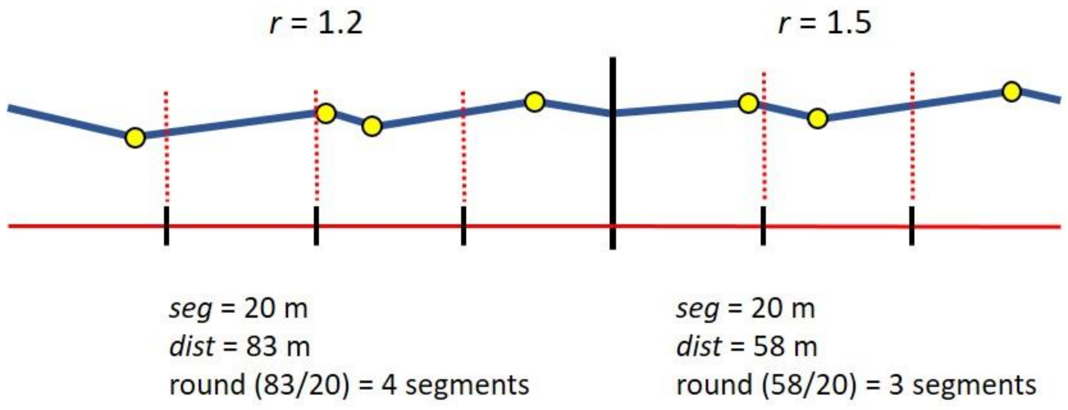


Figure 5.6: Polyline segmentation based on input distance value (seg) for a line with two different r values.

Figure 5.6 provides a visual example of how the division into equal size segments is realized. The line object (blue line) has segments of $r = 1.2$ (left side) and segments of $r = 1.5$ (right side). The blue segments delimited by yellow points are individual (straight) line segments. The segmentation into sections of equal length (red line) is performed using the above described formula. For a polyline of 83 meter length (*dist*), a *seg* value of 20 will for example result in a four segments of equal length with approximately 20 meters. In case a line segment has been divided into segments, the points on the original line that intersect with the dotted red line in Figure 5.6 are used as starting point $P_a(x_{a,} y_a)$ and end point $P_b(x_{b,} y_b)$ for calculating new point location(s) as part of the distortion procedure.

Figure 5.7 shows how the shape of the resulting distorted line can differ depending on the specified length for segment division (with data-based calculation of d). While a value $seg = 5$ meters yields a very strong level of distortion, making it hard to distinguish individual *spikes* of the line, with increasing segment length, the resulting line becomes less jagged, with clearly visible individual line segments. This difference in intensity of distortion may also be relevant in the context of adapting the map representation to ensure visibility of distortions at different scales.

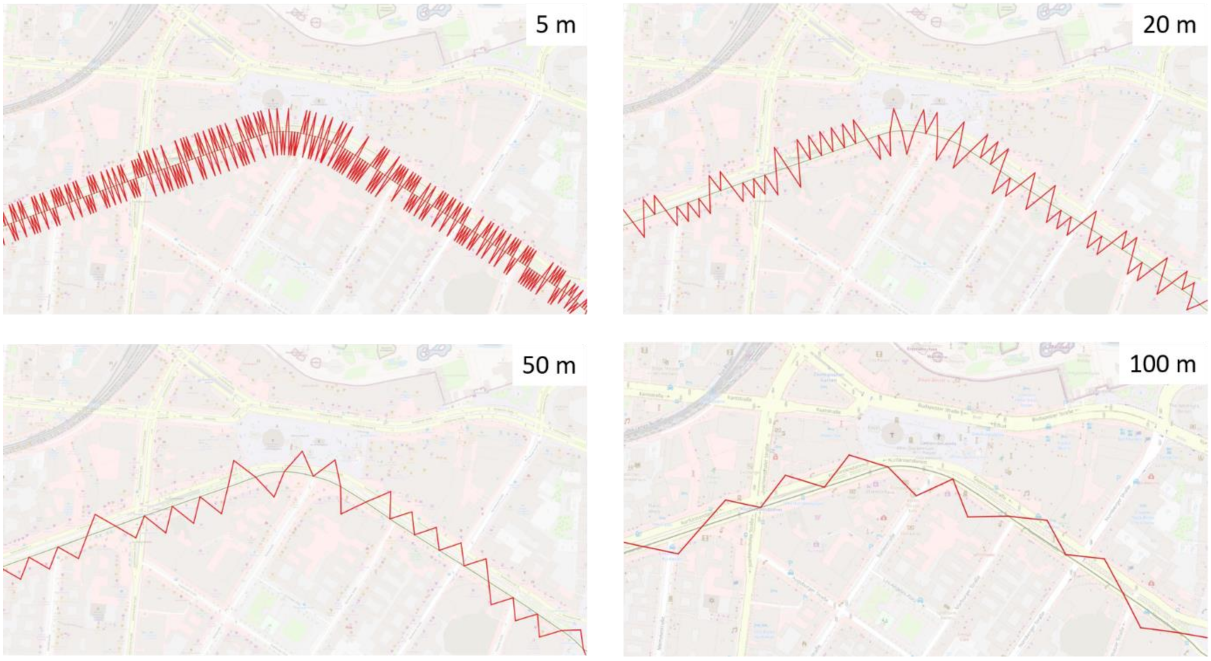


Figure 5.7: Line variations based on definition of segment length for segment division (factor seg). Map data from Open-StreetMap.

The visualizations show that a value of *seg* = 20 (meters) may provide visually pleasing results, since individual distortions are clearly visible as such. However, this may depend on individual preferences or the purpose of applying the distortion. Additionally, the visual results for different lengths of segment division may also vary depending on the input data. In case of inserting one new point for each line segment and specifying a value of 20 meters as a length for segment division, the *fs* value would always be around 10 meters (with small variations due to the randomization factor). In case a polyline is shorter than the specified length for segment division, a shorter relative distance from the starting point to the base point *F* is calculated, according to the calculation of the parameter *fs*.

Standard implementation and variants of the algorithm

After intensive testing of the effects of different parameter specifications on the visualization result, the following standard implementation of the algorithm is specified, which has been found to yield the visually most pleasing results, while adequately visualizing variations in the data values.

In the standard implementation of the algorithm, the distance parameter *d* directly depends on the data (factor *r*) as explained above, while the number of points to be inserted per line segment is set as a fixed factor (one point inserted for a segment of a standardized length).

In addition to the above-described standard definition of the used parameters, two variants of the algorithm have been defined, with the main intention to make the approach more flexible. The variants involve the following specifications.

1) Both parameters *np* and *d* are defined depending on the data, as explained above.
2) The parameter *np* is defined depending on the data, while parameter *d* is defined as a fixed value.

Figure 5.8 shows a visual example of variant 1) with data-based calculation of both factors *d* and *np*. In addition to variations in distance of the new points to the line caused by parameter *d*, more points are inserted at parts of the line with large *r* values, making these parts of the line looking particularly jagged.

Figure 5.8: Visualization using data-based calculation of both factors d (distance from line) and np (number of points), polyline segmentation with seg = 20 meters. Map data from OpenStreetMap.

A visual example for variant 2) is not provided, since it is suggested to have less practical value for visualizing favorability in route maps.

Figure 5.9 compares the visualization results of the standard implementation with fixed number of new points with variant 1 using a data-based calculation of the number of points. The *r* values used for creating this example are the same as used in Figures 5.7 and 5.8. The insertion of multiple points per segment causes the line visualization to become extremely jagged and complex. However, this confusing type of symbolization might still be useful for various different phenomena when visually communicating to avoid a particular part of the environment.

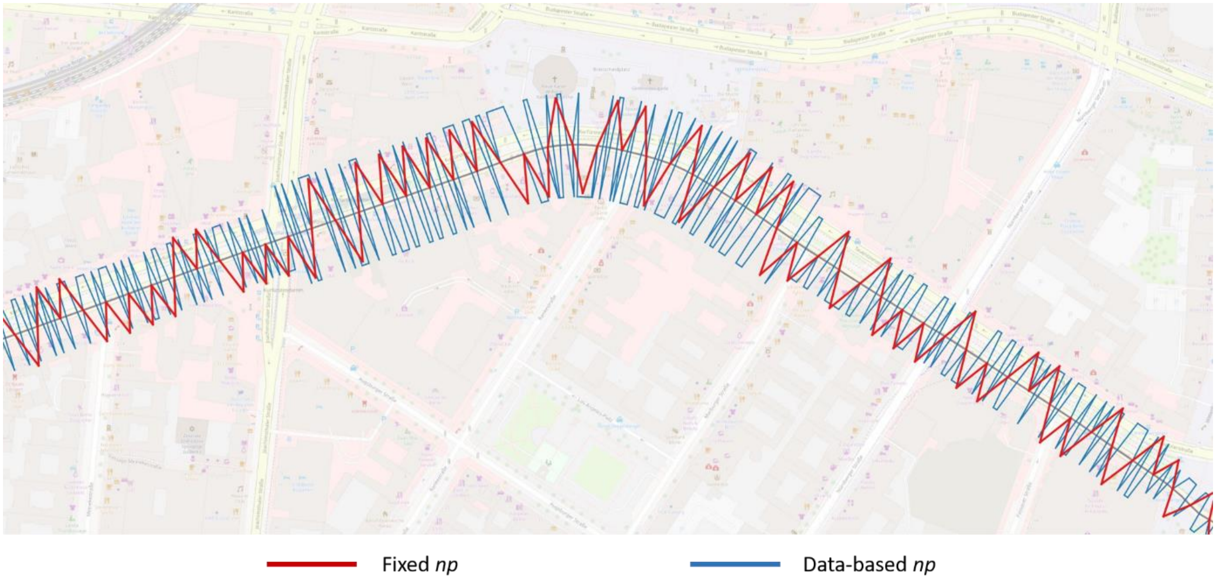


Figure 5.9: Comparison of the visual results for the standard implementation (fixed np) with variant 1 (data-based np) as a visual overlay. Map data from OpenStreetMap.

5.3.1.2 Line simplification

The line simplification approach is based on the idea of the Douglas-Peucker algorithm (see chapter 2.3.4.3 of this thesis for a detailed description of the original algorithm). However, instead of manually defining the ε value as a threshold for simplification, an automatic calculation based on the r value is introduced:

$$\varepsilon = dmax * (1 - r), \text{ with } r < 1 \quad (5.11)$$

The value $dmax$ describes the distance from an approximating straight line that connects the first and last point of the polyline to the point which is located furthest away from this line (perpendicular distance).

Consequently, a smaller r value will result into a larger ε value, and therefore to a stronger simplification of the polyline. A larger r value close to 1, however, will result into an only very slight modification, due to a very small ε value as a distance threshold for simplification. Similar as for the distortion part, introducing a weight factor $w > 0$ to the epsilon calculation can further regulate the intensity of simplification. With a weight value $w \leq 1$, the point on the original line corresponding to $dmax$ is always preserved for any $r < 1$. With a weight value $w > 1$, the value for ε can be larger than $dmax$, which results in the curve being simplified to a straight line.

To enable the simplification procedure, line segments with the same r value are dissolved. Except from this data-based specification of the distance threshold ε, the line simplification approach for simplifying the geometry of favorable route segments follows the procedure of the original version of the Douglas-Peucker algorithm (Douglas & Peucker, 1973) as introduced in chapter 2.3.4.3.

Figure 5.10 shows how different r values and weight factors can result in different levels of simplification of the input polyline. In case of $r = 0.9$, it can be noticed that only a very small part of the line has been simplified. With a smaller r value, ε increases, which results into a stronger simplification of the line. Due to the large $dmax$ value (distinct curve in the original line), in this example, a weight factor $w = 0.2$ is applied, in order to reduce the level of simplification in general, and therefore to enable showing visual differences resulting from the simplification. Different from the other three maps, the line simplification applied in the map in the lower right of the figure uses a weight factor of $w = 2$, which, in combination with the small r value, results in a very large threshold for simplification, larger than $dmax$. Consequently, the polyline is simplified to a straight line.

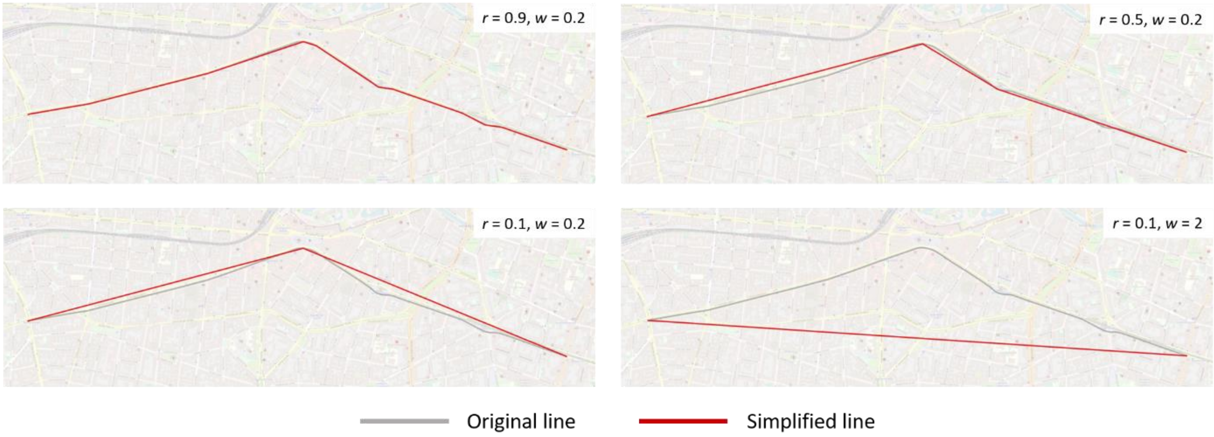


Figure 5.10: Impact of different r values and weight factors on the simplification of a polyline with data-based calculation of the ε value. Map data from OpenStreetMap.

5.3.1.3 Combined approach

Figure 5.11 illustrates a sample application of the combined distortion and simplification procedure to a set of roads in a real environment (gray colored lines). The different road segments have been assigned different *r* values that relate to different levels of favorability for traveling along a road segment. The yellow triangles point to the locations on the line at which the *r* value changes.

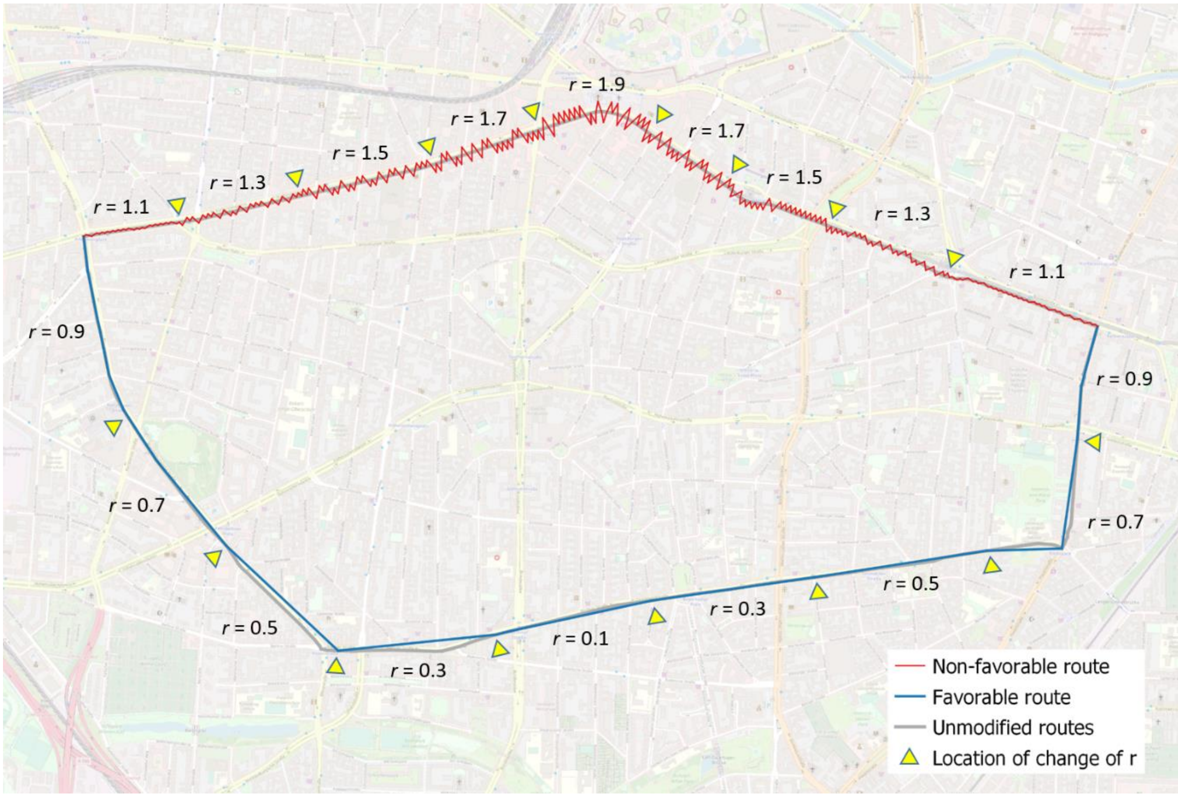


Figure 5.11: Application of the combined distortion and simplification procedure to a set of roads in a real environment. Map data from OpenStreetMap.

It is clearly visible that for favorable (blue colored) road segments, the simplification procedure is applied, while for non-favorable (red colored) road segments, the distortion procedure is applied.

For the distortion part of the generalization procedure, the previously described standard implementation is used, which means that each one new point is inserted per segment of equal length, while the distance between the new point and the original line is calculated based on the input data.

Regarding the simplified segments, it is visible that because the line segments with the same *r* value already have a structure relatively close to a straight line, in many parts of the polyline, only minor simplifications are performed. This makes it also difficult to distinguish different intensities of simplification that are due to different *r* values. Regarding distorted line segments, factor *d* ensures a larger distortion for road segments that are less favorable, while for *r* values close to 1, only very slight distortions are observable.

5.3.1.4 Topological issues and further adaptions

The implementation of the combined distortion and simplification algorithm further accounts for solving topological issues such as the preservation of intersections. Furthermore, in case the line geometry includes disconnections (e.g. due to errors in the data), the implementation uses a function for fixing these topological errors.

When applying the proposed distortion technique to very complex line objects, such as curves, the algorithm in its current form is mostly capable to avoid cases of self-intersection, but it is still possible to occur. Hence, the implementation of the algorithm may need to be improved in this direction.

Additionally, when applying this method in an interactive digital map, an adaption of the visualization to changes in the map scale is required to ensure a visually appropriate representation of the modified line objects. Empirical testing has shown that a value of *seg* = 20 can serve as an appropriate parameter that may yield visually pleasing results for different zoom levels. However, an automatic adaption of different parameters is suggested to be reasonable for providing effective and visually appropriate representations at different map scales.

A further adaption of the algorithm can be related to creating a more regular distortion, which may provide more suitable visualization results for some use cases. This involves replacing the randomization regarding at which side of the line a new point is inserted by alternately inserting new points at the left and right side.

5.3.2 Length distortion using PUSH

In addition to the previously presented *distortion* approach, the *length distortion* approach has been developed as a further method for polyline generalization as part of this thesis.

The motivation for developing an algorithm that automatically distorts the length of a given line segment is based on findings from cognitive psychology research related to the assumption that travelers perceive road length depending on the travel time related to viscosity of traffic, rather than the correct metrics of a road segment (Saedi & Khademi, 2019; Golledge & Zannaras, 1973, MacEachren, 1980). Figure 5.12 shows how the perceived distance between two locations along a route may deviate from the actual metric distance, depending on a temporary factor such as traffic conditions. In contrast to the metric distance between two points along a road segment, the perceived distance is not easily measurable in terms of metrics, since it is not a fixed value and varies depending on individual differences in human perception of space and time.

Although the idea for applying this method is based on the traffic congestion scenario, the proposed approach is applicable to other types of environmental phenomena, since the modifications to be performed for this visualization approach are also based on the previously introduced factor *r* that describes the ratio of an observed value and a predefined threshold value (see Eq. 4.3).

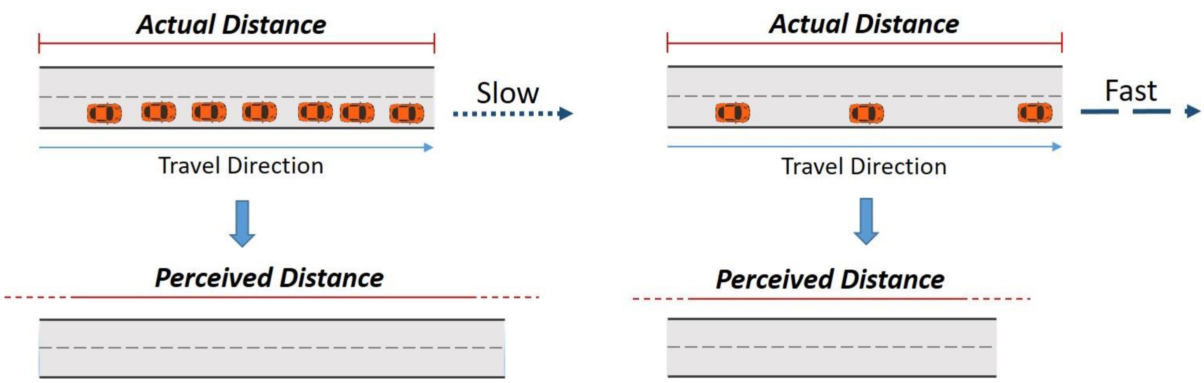


Figure 5.12: Actual length of a road segment as compared to the perceived length.

In order to distort the length of a line segment, the PUSH software (Sester, 2006) is used, which has an *enlarge* functionality to scale objects by a factor. PUSH is a software program originally developed for automatically generalizing cartographic objects, particularly for removing spatial conflicts by means of displacement. In addition to the *enlarge* parameter, furthermore, the parameters *aura*, *stiffness* and *pushable* are required for performing the displacement procedure. Please refer to chapter 2.3.4.3 for a detailed description of the parameters and the capabilities of the program PUSH.

For automatically determining the *enlarge* factor, the calculation is simply based on the *r* value assigned to the line segment. Furthermore, a weight factor $w > 0$ is introduced, which allows for more flexibility in attempting to achieve visually pleasing results, while still ensuring a data-based calculation of the *enlarge* factor. The weight factor can be specified manually. By default, the factor is set to $w = 1$.

$$enlarge = w * r \tag{5.12}$$

The resulting polyline scales the individual line segments based on their indicated favorability (assigned *r* values). That is, unfavorable line segments are enlarged, whereas favorable segments are reduced in length. In case of a neutral level of favorability ($r = 1$) with a weight factor of $w = 1$, the *enlarge* factor does not have any influence on the visualization of the segment.

In the following, the impact of the enlarge factor on route map visualization results is tested. For this, it is evaluated how the software performs and handles geometric conflicts in three different cases: 1) Modification of a single polyline, 2) Modification of multiple polylines representing two routes with adjacent roads, and 3) Modification of an entire road network and land use areas of a specified region.

For all three cases, the values for the parameters *aura*, *pushable* and *stiffness* are set to a very small number close to 0, in order to ensure a maximum level of flexibility for deforming spatial objects. As *enlarge* factors, two different values are used for the test examples: *enlarge* = 2 for unfavorable line segments that should be increased in length, and *enlarge* = 0.5 for favorable line segments that should be decreased in length.

Figure 5.13 shows the application of the approach to a single polyline. While the line segments left of the yellow circle are assigned an *enlarge* value of ‘2’, segments right of the yellow circle are assigned an *enlarge* value of ‘0.5’.

After executing the PUSH program with the described parameter specifications, the geometry of the resulting, scaled line segments indicates that when visualizing one single polyline, the program scales the individual road segments quite reliably depending on the input value for the *enlarge* parameter, since only minor geometric conflicts need to be solved.

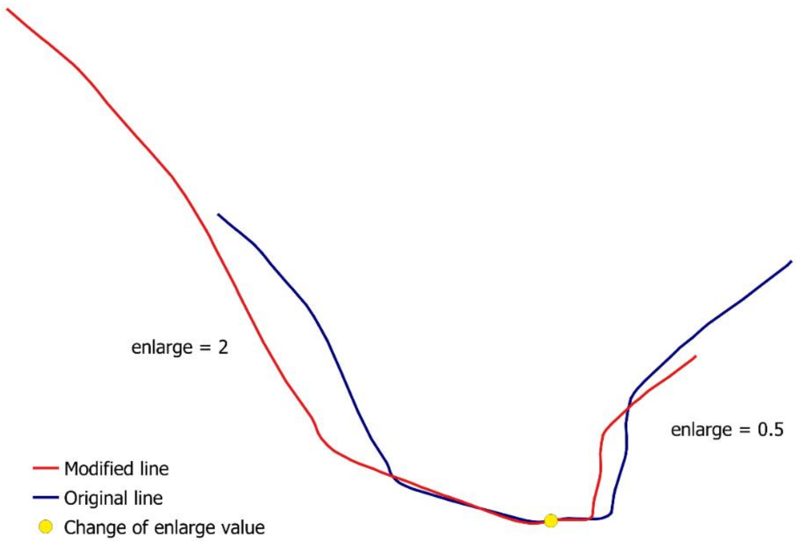
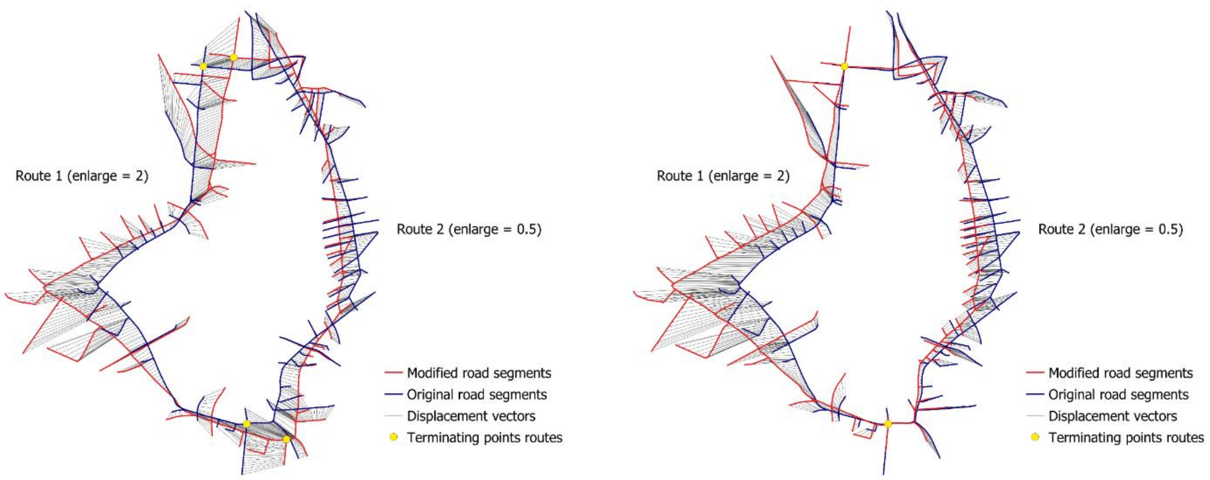


Figure 5.13: Effect of the enlarge factor on the distortion of line segments for a single polyline.

Application to multiple routes

Since in this research, visual modifications are not only intended to be applied to individual polylines that represent a single route, but also to multiple routes that share the same start and end point, the application of the PUSH procedure for modifying multiple, adjacent polyline objects, is tested. Figure 5.14 (A) shows the original geometry of two routes with additional adjacent road segments, as compared to the modified geometry of the same polyline objects. In addition to the line segments, the terminating points of the routes and the displacement vectors for representing the changes in the geometry of objects, are visualized. The original length of Route 1 is slightly shorter than the original length of Route 2. However, when applying geometric deformation using the specified *enlarge* factors for the two routes including adjacent road segments, they are scaled in a way that after modification, Route 1 appears longer in distance and consequently less favorable than Route 2. Thus, the desired effect is achieved.



A B

Figure 5.14: Effect of the enlarge factor on the distortion of multiple line segments (routes), without (A) and with (B) fixing the position of the start and end points of the routes.

When modifying single polyline objects, a line segment that has been assigned an *enlarge* factor of ‘2’ is likely to be scaled – as desired – with twice its original length, however, the same behavior is not expected to be observed for multiple connected objects. That is, because the system tries to satisfy all constraints in an optimal way. Therefore, it is not possible to avoid additional distortions that occur due to mutual constraints regarding multiple objects, while still retaining the original topology of the road network. One possibility to partly control this behavior is to fix selected objects, so that they remain at their original location and are not affected by any distortions. This is achieved by setting the *pushable* value of an object to a value of -1. In this case, the object is not moved, since it is not considered during the generalization process. Additionally, it is possible to fix individual points of an object at a certain position by introducing additional fix points. In Figure 5.14 (B), the start and end point of both routes is fixed. As a result, line segments close to the fix point are likely to undergo only slight geometric modifications, while segments of the polyline that are further away from the fix point are likely to be shifted and distorted even more distinctly. A side effect of this method can be that with fixing points, it becomes more apparent that the modified Route 2 would appear to be more favorable than the modified Route 1.

Geometric deformation of road networks

Figure 5.15 shows the application of the PUSH software to a road network consisting of a considerable number of line segments. Additionally, polygon objects that represent land use areas in the region of interest are considered as part of the generalization procedure. All individual objects of these two different types are assigned a specific *enlarge* value and are scaled based on this factor. The geographic objects shown on the left side of the map (red colored roads) are assigned an *enlarge* value of ‘2’ (non-favorable), while objects on the right side (blue colored roads) are assigned an *enlarge* value of ‘0.5’ (favorable).

Figure 5.15: Geometric deformation of an entire road network and land use areas in a specified region using PUSH.

Results after the scaling (*Modified*) show clear distortion in both the road network, as well as the land use areas, while still retaining topological relations between objects. As desired, non-favorable objects are visualized as larger, resulting in seemingly longer travel distances. Favorable objects, on the other hand, are visualized as smaller, resulting in a more dense structure and seemingly leading to shorter travel distances. The resulting, generalized road map shows roads at different scales within one map, which provides an effect that is similar to the concept of a variable-scale map as applied by Haunert and Sering (2011).

5.3.3 Application to discrete areas: Geometric deformation of risk zones

A further cartographic generalization technique that has been developed in the context of this research work, intends to apply geometric deformation of map objects in a way that an illusion of a 3-dimensional distortion is created for symbolizing discrete risk zones (Shkedova, 2021). A risk zone can for example relate to an area of negative impact that is hazardous to the environment, including areas with increased air pollution or other types of areal contamination. The idea behind this approach is to deform road segments in a way that it might be perceived as an illusionary 3-dimensional pit or pothole placed on a 2-dimensional map. Pits and potholes are often desired to be avoided by travelers due to an increased risk of damage or additional effort required when traversing such an area (Zipf, 2016). Based on this motivation, a higher risk associated with the communicated phenomenon is symbolized by applying a stronger deformation and hence creating an illusion of a deeper pothole or pit. Accordingly, a stronger deformation of the road network within a risk area is expected to lead to a stronger motivation to abstain from the area that is communicated as dangerous.

Different from the previously explained length distortion approach, which also applies distortion to road networks, the geometric deformation of risk zones is performed based on a pre-specified discrete region with clear boundaries.

The definition of the extent of a risk zone is based on the geometric characteristics of the source of negative impact. This could for example relate to point geometries (e.g. single chimney), line geometries (e.g. pollution measured along the road), or polygon geometries (e.g. industrial area).

Risk zones are created by building buffer areas around the geometry objects that serve as a source of negative impact. Specifically, this procedure involves completing the following steps:

1) Build buffer with a specified radius around each geometry object
2) Dissolve overlapping buffers (leading to risk zones), calculate the mean *r* value (see Eq. 4.3) for each risk zone, remove zones with mean r ≤ 1
3) Clip roads from road network within risk zones
4) Save road network after clip

Figure 5.16 shows several point-based locations of negative impact (green-colored points) that are combined to different risk zones by dissolving overlapping buffers. Consequently, the resulting risk zones can have arbitrary shapes. The figure shows the dissolved risk zones before applying the morphological operation *closing*, which simplifies the shape of the risk zones of multiple dissolved buffers. Such simplification helps minimizing an intersection or overlap of deformed roads inside the zone. For example, topological issues are resolved such as small holes inside the resolved buffer area and a smoothing of the buffer outline.

Figure 5.16: Definition of risk zones by dissolving buffer areas around locations of negative impact.

Importantly, also for this approach, the described *r* value refers to the ratio of the observed value and the threshold, as introduced in equation Eq. 4.3. Accordingly, this means that a risk zone only includes road network parts with values that are on average considered as not favorable (*r* > 1).

For applying deformation of risk zones, two different approaches are proposed: 1) Multi-scale deformation and 2) concave lens deformation. In both cases, the resulting geometric deformations intend to give an impression of a pit or pothole within the environment.

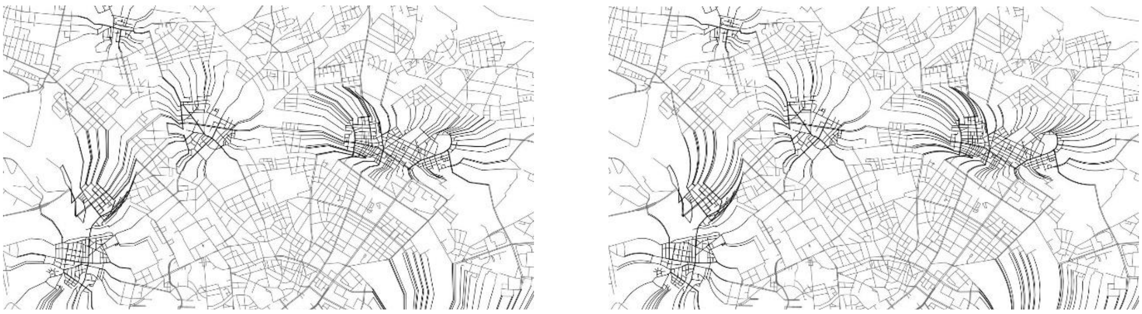
The multi-scale approach is based on perspective drawing art techniques as featured in D’Amelio (2004) for achieving a visual effect of depth. The approach involves as a first step that the road network within the risk zone is scaled down based on the input *r* – values. A lower favorability (e.g. higher level of pollution) causes the scaled road network to be represented as smaller in size. To ensure applicability to different input datasets, scaling is performed based on a normalization (between threshold value and maximum observed value).

In a second step, the scaled down area is shifted along the y-axis from the original position in the center of the risk zone towards the border of the area. With a higher *r* value, the scaled down area is shifted closer towards the boundary.

After the road objects inside the risk area have been scaled to a smaller size, they need to be re-connected to the remaining road network that is not affected by a risk, in order to retain topological relations between road segments. To achieve this, additional line segments are introduced as connectors between the road segments of the original roads and the scaled roads that got cut off during scaling. Two different types of connectors are proposed, which intend to intensify the impression of depth when viewing the deformed visualization: a *knee* connector which involves a sharp bend (technique based on the line distortion approach described in chapter 5.3.1.1), and a *curve* connector (using Bezier curves), which describes a smooth curve.

All three described characteristics of the deformed road network (degree of the scale, shift, and curvature of connection lines) depend on the level of risk inside the zones. The higher the negative effect in a risk zone, the smaller the scale, more significant the shift, and the steeper the curvature of connection links. Since with increasing *r* values, the scaled down area gets smaller, consequently the connectors are enlarged. In the extreme case (maximum value after normalization), the scaled area is extremely reduced in size, so that it nearly vanishes, which causes the connectors to almost meet at one point.

Figure 5.17 shows the application of the *multi-scale deformation* approach to several risk areas of different shapes and different risk level, after applying the morphological operation *closing*. The scaled road network in the risk zones in Map A is linked to the unmodified road network outside the risk zones using *knee* connectors, while in Map B *curve* connectors are used for creating an illusion of depth. Furthermore, to visually intensify the depth illusion, it is possible to add a shading to the risk zone visualization. An example of such a visual representation is provided in a map representing the design variant *Deformation (Dfr)*, as prepared for user study 3 described in chapter 6.3.3.



A B

Figure 5.17: Application of the multi-scale deformation approach to several risk areas of different shapes and different risk level. A = knee connector, B = curve connector. Risk area deformation in both maps corresponds to the risk areas as defined in Figure 5.16.

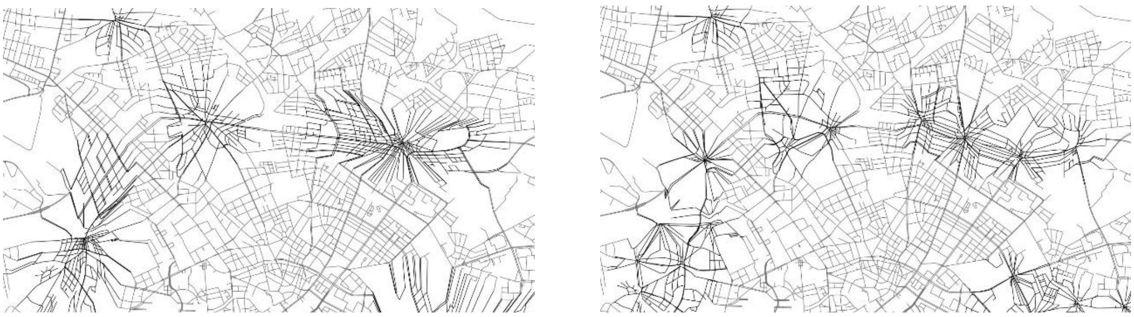
As the second deformation approach, the concave lens deformation method as introduced by Yang and collaborators (2005) is adapted to the case of geometrically deforming risk zones. Accordingly, roads inside the risk zone are projected on a plane by a virtual concave lens. The size of the lens depends on the maximum radius of the risk zone.

The general principle of this approach consists of rays, which pass the concave lens from the start and endpoints of each road segment, are altered and reach the plane. Consequently, new re-projected positions are defined. The implementation of the deformation required the transformation of the road segment coordinates to the local coordinate system of each zone with the origin in the center. The degree of lens concavity for projection is defined by varying the parameter *f*, which is experimentally set depending on the average favorability (*r* value) of the road segments within the risk area.

The deformations that are created based on the input data in this approach can either be performed using a *mono-focal projection* or a *poly-focal projection*. The mono-focal projection uses one focal point in the risk zone center and the intensity of deformation is based on the average risk level (*r* value) in the entire risk zone. In case of a poly-focal projection, there are multiple focal points for applying the projection, which each represent the individual point objects describing the different sources of negative impact within a risk zone. In case a risk zone includes only one point as a source of negative impact, then the projection is performed in the same way for both variants of the approach.

Figure 5.18 shows the application of the *concave lens deformation* approach to several risk areas of different shapes and different risk level. While Map A shows the deformation using mono-focal projection, Map B uses poly-focal projection.

For both the multi-scale deformation and the concave lens deformation approaches, it is possible to further intensify the optical illusion of depth by applying visual variables as depth cues such as color, size or shading.



A B

Figure 5.18: Application of the concave lens deformation approach to several risk areas of different shapes and different risk level. A = mono-focal projection, B = poly-focal projection. Risk area deformation in both maps corresponds to the risk areas as defined in Figure 5.16.

5.4 Examples of route map design variants

Based on the previously introduced visualization concepts for designing *social* route maps, different types of cartographic symbolization can be applied to communicate the urgency of avoiding roads or areas with increased observed values that are unfavorable based on the communicated phenomenon. In the following, a set of examples of possible route map design variants is presented including symbolization of both line and area objects, for visually communicating route favorability based on data related to pollution levels. Although the used map symbols and visual variables allow a wide range of further possible design variants for communicating suitability of route options with respect to pollution values, seven map variants are exemplarily (Figure 5.19 a-g) provided that either use visual modification of linear map features, areal map features, or a combination of both, in different ways. Additionally, although pollution levels are used as input data for creating the route map visualizations, the application of the map design and the used types of symbolization are not limited to this specific environmental phenomenon, but can (from a methodological point of view) be applied to further traffic related or environmental scenarios.

The seven resulting map representations depict the same spatial extent and use the same input data for producing graphical differences in symbolization. In particular, they relate to the interpolated $PM_{2.5}$ pollution within the city of Berlin – as presented in Figure 4.4; while the two route options directly result from the two different routing approaches (route option 1 = regular routing, route option 2 = pollution avoiding routing).

In the following, the visual characteristics used in the different design variants for communicating favorable and non-favorable route options are explained in detail.

5.4.1 Design variants for symbolizing route favorability

All map representations (except the one using variations in intensity value for route visualization) use blue color for visualizing route options, while showing the surrounding road network using a light grey color shade to make it look less prominent as compared to the routes that should stand out to the map-reader. Additionally, the start and end point of the routes are symbolized by unique icons (car symbol for the start location and flag symbol for the target location). An additional base map layer from *OpenStreetMap* intends to facilitate spatial orientation in the area of interest. However, the opacity of the base map has been reduced, in order not to distract from the symbolization used in the maps. To possibly enhance user-friendliness of the route maps, additional textual information, such as travel time information, could be added next to the route visualization.

While route option 1 refers to the suggested route using regular routing, route option 2 additionally takes the $PM_{2.5}$ concentration into account, and therefore circumvents the area with a critical level of air pollution. Obviously, this favorable route option results into the longer route (by travel time and distance). Therefore, the objective of this representation is to apply visual variables to map symbols in a way that the longer, but recommended route visually appears as more desirable and more reasonable to choose. For the shorter and potentially faster route, however, the used symbolization intends to point out that the route should be avoided by visually highlighting the possible hazards associated with choosing the route. Since for example in the case of the *air quality* scenario, the proposed routing approach for the *societally favorable* route calculates the fastest route while avoiding areas with increased particulate matter concentration, it is possible that even the favorable (longer) route option marginally touches the critical area that is intended to be avoided.

Although different types of symbolization are applied for all seven proposed design variants, they all intend to visually communicate the same information. Based on the used input data, the communicated information could relate the level of air pollution, but it could potentially relate to different environmental information, in case a different scenario involving different data is addressed. In case of air pollution, all applied visual variables serve as a metaphor for symbolizing a layer of emissions, similar as proposed by Boy and collaborators (2015). In the following, the visual characteristics of design variants of route maps are exemplarily explained with regard to the *air quality* scenario.

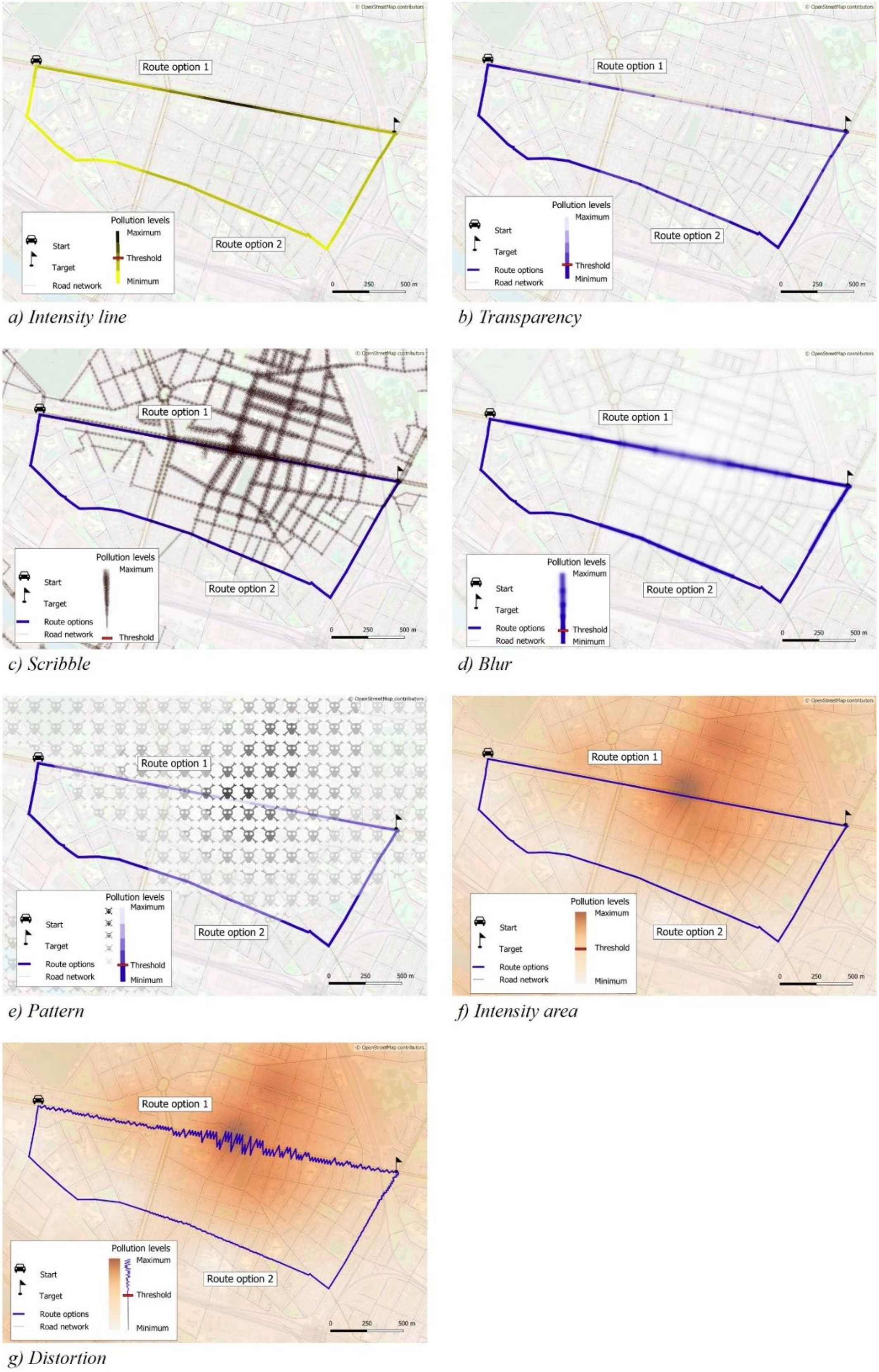


Figure 5.19: Map examples showing different methods for visually communicating the impact of pollution levels on the reasonableness of choosing an individually efficient, fast route (Route option 1) or a societally favorable route that reduces exposure to highly polluted areas (Route option 2). Map data from OpenStreetMap.

Intensity line

In addition to previously introduced common map characteristics, the variant *intensity line* (map a) visualizes the route options while showing differences in the intensity value (yellow color) depending on variations in pollution levels. While the most favorable parts of route options are visualized using a pure, yellow color, non-favorable parts of the routes are represented by a brown shade that intends to give the viewer the impression of impurity at the corresponding parts along the route. The dark yellow or brownish color directly corresponds to how the human eye may actually see strongly polluted air (Koenig, 2000).

Transparency

Similar to the previously described map, the variant *transparency* (map b) also uses visual modifications only for the line segments of the provided route options. In this map, variations in pollution levels are presented using different levels of transparency. In particular, favorable route segments that are associated with values below the set threshold are always shown in full opacity, while non-favorable route segments are visualized with increasing transparency. Consequently, very critical parts of a route would be visualized with very high transparency – making these parts of the line hardly visible. This representation is suggested to be suitable for visually communicating air pollution levels, since the “faded” parts of the route are proposed to give an impression of moving through a fog or cloud layer of emissions (MacEachren, 1992).

Scribble

As a further visualization type, the variant *scribble* (map c) adds scribble (or noise) to road segments (Carroll et al., 2020) that are located within highly polluted areas. It is created as an additional layer – overlaying the road network and route visualizations. The stronger the threshold is exceeded, the more scribble (with larger size) is added to the corresponding road segment. In this design variant, the road network within areas that fall below the threshold value is not affected by the use of visual modifications. With this method, less favorable parts of the road network and the route options are intentionally obscured – by providing an impression of a layer composed of emissions on top of the road network.

Blur

The variant *blur* (map d) communicates non-favorable parts of the road network that should be avoided, by adding a blurring effect. The blurring intensity varies in a way that the road network and route options located in an area related to the maximum pollution level, are visualized as very blurry, while map objects in areas that only slightly exceed the threshold are visualized using minor blurring. Areas that fall below the threshold are not affected by the use of the blurring effect. It is important to note that map parts that are rendered with a higher blurring intensity are consequently less legible. While in cartography, the blurring effect is commonly applied for communicating levels of uncertainty (MacEachren et al., 2005; Kinkeldey et al., 2014), this type of visualization can further be associated with a cloud layer (of emissions) that impedes visibility.

Pattern

The variant *pattern* (map e) uses a pattern composed of icons of varying opacity for showing variations in pollution levels. While there are options for further possible icons (e.g. cloud icons for symbolizing emissions), in this example, a skull icon is used, since it could potentially be used for communicating the severity of a hazardous phenomenon. In many cultures, the skull icon is associated with increased danger (to life) or with hazardous objects or phenomena. Depending on the pollution level associated to the respective area, the degree of opacity of the icon color (full opacity = black) varies. Areas with maximum observed particulate matter pollution are filled with icons visualized at full opacity, while areas that fall below the threshold are not overlaid by pattern. Similarly, road segments and route parts are visualized with varying opacity. In this case, however, the symbolization is applied in the opposite way: Roads crossing highly polluted areas are visualized with very high transparency, while roads that cross areas with values below the threshold are visualized with full opacity. This effect intends to enhance the impression of a potentially hazardous cloud layer that has settled over the area – while particularly pointing to the parts that are most severely affected. In addition to using different gradations of *transparency* for showing differences in pollution values, the icons can further be combined with variations in *size, color value*, or further variables.

Intensity area

The variant *intensity area* (map f) uses a color scale (visual variable *intensity value*; dark orange color for areas with increased pollution values and light orange color for areas with lower pollution values) for visualizing pollution levels in the different areas, while the route options themselves are not modified. Similar to the *intensity line* variant, here, the color choice also intends to correspond to how the human eye sees polluted areas (Koenig, 2000).

Distortion

The route map variant *distortion* (map g) combines the symbolization of lines (for the route segments) and areal features on two different levels. While the same color scale is used as in map f) for visualizing pollution levels in the different areas, an additional modification of the geometry of the line segments that are part of the routes, is applied (visual variable *distortion*). Both types of symbolization intend to complement each other in a way that the intensity of distortion of the modified route directly corresponds to the variations in intensity value of the area the routes are crossing. The maximum level of distortion as visualized in the map corresponds to the dark orange and symbolizes the maximum observed pollution level. In case the pollution level equals the threshold value, no line modification is applied. However, the geometry of route segments that cross areas below the threshold is simplified, while reaching the maximum degree of simplification (modified to a straight line) for the minimum pollution levels (Fuest et al., 2021). In the example, the line simplification of route parts that cross less polluted areas is less apparent, since the original geometry of the affected segments has already been relatively close to straight lines. While the used color scale relates to a widely applied symbolization for showing spatial differences in areal features, adding distortion to the lines intends to intensify the impression of unfavorable route segments due to the pollution distribution.

In addition to the provided map examples, it is possible to create further map variants using the proposed graphical differences for applying visual variables to map symbols. Possible combinations may involve showing variations in line size together with variations in intensity value of the background map, or presenting a distorted line in combination with a blurring effect.

5.4.2 Application of the methodology to discrete objects

The use case related to particulate matter pollution, as described earlier in this chapter, deals with an areal, continuous phenomenon. As mentioned earlier, the application of the proposed method is not limited to continuous objects, but can also be applied to discrete objects in a similar manner, such as traffic jam prone areas, accident blackspots or entire neighborhoods to be avoided for various reasons.

A practical example for areal, discrete objects is to communicate the avoidance of driving through a city center – for example in case of a critical event, or for ensuring safety of pedestrians, cyclists or other vulnerable road users (Darko et al., 2022). Figure 5.20 provides a map example demonstrating a potential application of the proposed visualization method to discrete objects. In the map visualization, two distinct 'prohibited areas' of different size and shape are declared. Importantly, although being denoted as *prohibited*, it is still possible for drivers to cross these areas, but it is recommended to be avoided. Both areas have in common that the *observed values* exceed the *threshold* within the boundaries of these areas. For communicating the urgency of avoiding to drive through the prohibited areas, a combination of *blurring* (for visualizing favorability of road segments) and line *distortion* for representing the boundaries of the areas, is applied. A higher urgency of avoiding the prohibited areas (higher value *r*) is visually communicated by a higher level of blurriness and a greater distortion (as visible for the larger area).

While the automatic calculation and symbolization of suitable routes based on environmental phenomena can be generalized across different scenarios, the usefulness of the design variants as proposed for a specific scenario such as air pollution may differ for other scenarios, such as the avoidance of the city center. That is, because the intuitiveness of the used symbolization is suggested to differ depending on the communicated phenomenon.

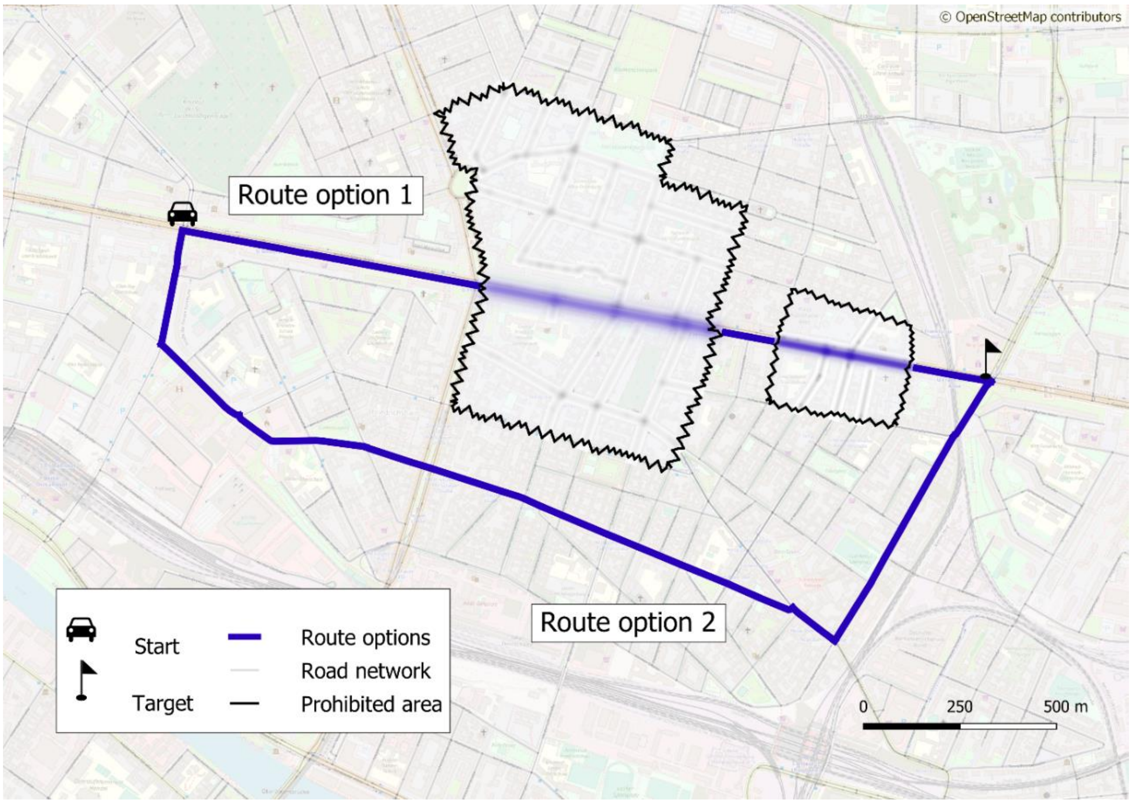


Figure 5.20: Map example demonstrating the application of the proposed method to discrete objects (two city districts to avoid by car traffic). Map data from OpenStreetMap.

6 Usability evaluation of proposed route map design variants

While the previously described methodology allows to automatically create route maps that show favorability of routes using cartographic symbolization, it is crucial to investigate how the usability of the proposed visualizations is evaluated by potential users. In this chapter, the applicability of proposed design variants of route visualizations is evaluated by conducting three different user studies that test subjective and objective usability. Subjective usability is tested by one user study (user study 1), asking participants to evaluate graphical attractiveness, intuitiveness, and suitability of a visualization for representing the communicated phenomenon (see chapter 6.1). Objective usability is assessed by two user studies (user study 2, user study 3), measuring the effectiveness and efficiency of a map symbol, with a focus on its effectiveness for influencing route choice (chapter 6.2, chapter 6.3). Additionally, in user study 3, emotional responses to map symbols are measured, with the purpose of assessing their influence on route choice decision making.

User study 1 investigates attractiveness, intuitiveness, and suitability of different design variants of route visualizations for symbolizing air quality information. User study 2 investigates effectiveness of visual variations of line objects for influencing route choice in the *traffic* scenario, while finally user study 3 investigates the impact of visual communication and emotional responses on route choice decision making using modification of line and area objects in the two different scenarios *traffic* and *air quality*.

In each of the three user studies, a set of sub-hypotheses is defined, which are refined to more specific hypotheses based on the overall key hypotheses of this thesis presented in chapter 1.2.

For each user study, a description of the experiment design and the results is provided first, followed by a discussion of the findings of the respective study. An overall discussion of the findings related to this thesis is presented in chapter 8 by comparing the relevance of the findings obtained from the different studies.

While the user studies described in this chapter focus on the evaluation of the proposed design choices for visually communicating favorability in route maps, a further usability test, which is described in chapter 7, focuses on evaluating user experiences made when interacting with route maps in a more realistic setup of a routing application.

6.1 User study 1: Subjective usability – Attractiveness, intuitiveness and suitability of design variants

User study 1 (adapted from Fuest et al., 2023a) validates the seven proposed design variants of route maps that have been introduced earlier (see Figure 5.19), based on criteria for subjective usability (Wielebski & Medyńska-Gulij, 2019), namely *intuitiveness, attractiveness* and *suitability* (Biadgilgn et al., 2011). For this study, the focus was on assessing subjective usability of different design variants for the *air quality* scenario, since, different as for the widely accepted traffic light metaphor for symbolizing traffic, there is no commonly accepted way of visualizing pollution levels on a map.

6.1.1 Sub-hypotheses

Prior to conducting the user study, two sub-hypotheses have been developed, which are derived from the key hypotheses introduced in chapter 1.2, and verified as part of the following analysis.

H 1:
"For representing areal phenomena in route maps, design variants using areal symbols are expected to be rated as more positive in terms of intuitiveness, suitability and attractiveness than variants using line-type symbols." (Derived from *Hypothesis 2*)

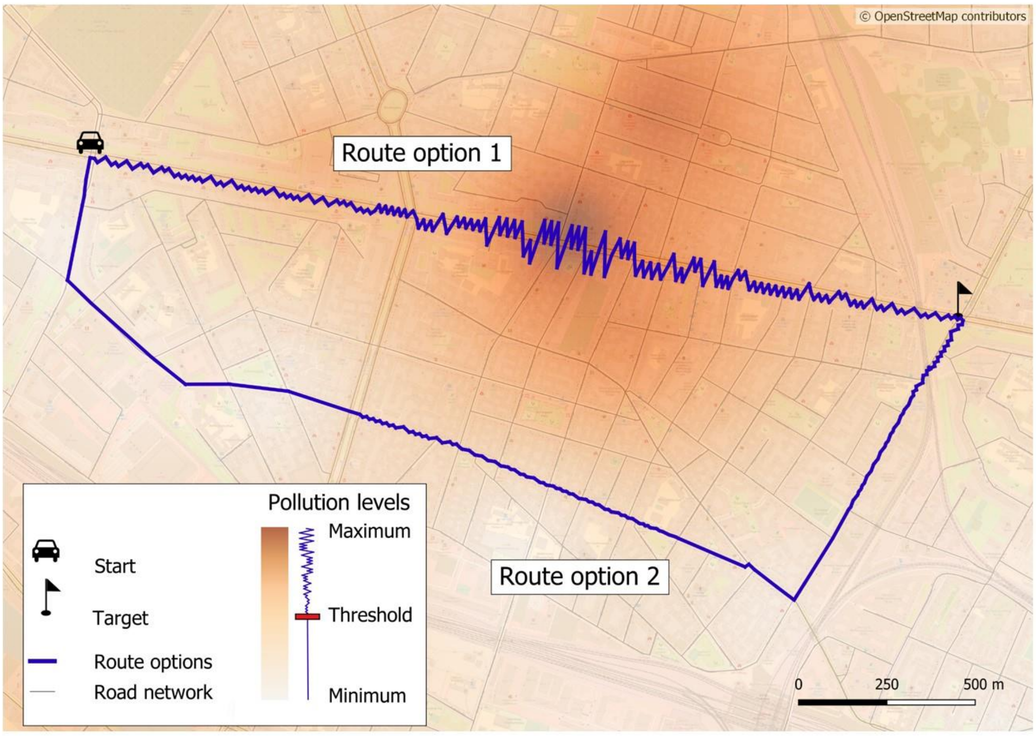
H 2:
"Design variants that are rated as "intuitive", are also expected to be rated as "suitable" for communicating air quality information." (Derived from *Hypothesis 2*)

6.1.2 Study design

To verify the hypotheses, an online survey has been conducted using a within-subjects design, which means that all participants completed the same set of tasks. The survey consists of two main tasks. In the first task, participants were asked to rate (for each map individually) the intuitiveness of the map representation and the suitability of the visualization for communicating air quality information. In both cases, a four point Likert scale was used (Intuitiveness: *very unintuitive, rather unintuitive, rather intuitive, very intuitive*; Suitability: *very unsuitable, rather unsuitable, rather suitable, very suitable*), which means that participants needed to decide for a certain point of view. The order in which the seven different maps have been shown was randomized. The task was introduced to the participants as follows:
"In the following you will see seven different map displays, each showing two route options. In addition to the route options, the level of air pollution is visualized on all maps by different representations. In each case, the symbol explanation indicates which symbol is used for areas that exceed or fall below the air pollution threshold. Your task is now to determine for each of the maps how intuitive the representation is to you, and how (in your opinion) the type of representation is suitable for the visualization of air pollution information."

Figure 6.1 shows an example of the experiment task with the two Likert scales placed below the map.

- How intuitive do you find the map?
- And how suitable do you find the representation for visualizing information on air pollution?



Very unintuitive	Rather unintuitive	Rather intuitive	Very intuitive
○	○	○	○

Very unsuitable	Rather unsuitable	Rather suitable	Very suitable
○	○	○	○

Figure 6.1: Example of task 1 of the experiment. Map data from OpenStreetMap.

In the second task, attractiveness has been assessed by performing a ranking of the seven different map visualizations. The survey concluded with a set of demographic questions, including gender, age, profession, experience in map usage and frequency of using navigation systems.

The invitation to the online survey has been shared on an e-learning platform for students at the authors' university, and has been distributed through various mailing lists with a focus on cartography experts from German universities.

6.1.3 Participants

In total, 98 participants (55 female, 40 male, 2 diverse, 1 not specified) completed the survey. Participants ranged in age from 19 years to 74 years (M = 28.42, SD = 11.39). The majority of participants were students (n = 71), while the remaining participants were employees (n = 24) or retired (n = 3). Since many of the participants have a cartography-related background, the level of experience in digital map usage is relatively high: 19.4 % experts, 58.2 % rather much experience and 22.4 % rather little experience. No participant selected the option 'no experience'. Regarding the use of navigation systems and routing applications, the majority of participants indicated being frequent users (60.2 %), followed by a rare use (30.6 %) and a use on every trip (7.1 %). Only 2 % indicated to never use navigation systems or routing applications. Hence, most of the tested participants could be potential users of an application using the proposed route map visualizations.

6.1.4 Results – Intuitiveness and suitability

The results of this study were analyzed with a focus on testing the hypotheses. Results regarding the intuitiveness of the map representations and their suitability for communicating air pollution information have been analyzed and compared based on the data resulting from the 4-point Likert scales. Figure 6.2 shows each one stacked bar plot for *intuitiveness* and *suitability*, visualizing the percentage of the level of intuitiveness or suitability. The bars of the design variants in the *intuitiveness* plot have been arranged in descending order, showing the variant with the highest percentage for *very intuitive* on top. For better comparability, the *suitability* plot has been arranged in the same order.

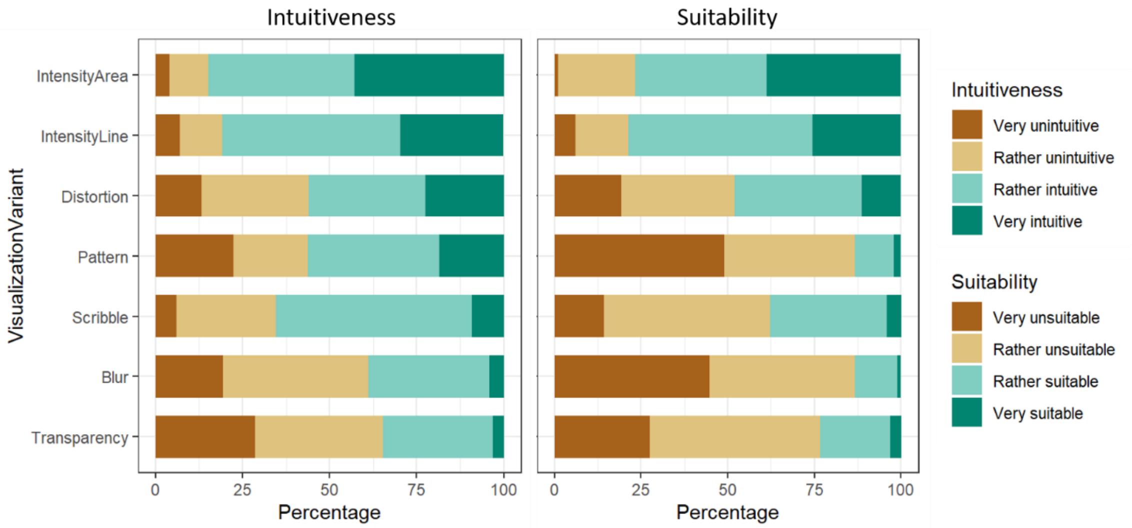


Figure 6.2: Intuitiveness and suitability rating for the seven proposed visualization variants of route map designs in percent, based on the 4-point Likert scale.

Results reveal that the design variants *Intensity area* and *Intensity line* have been primarily rated as intuitive. The variants *distortion, pattern* and *scribble* also have been perceived as relatively intuitive. The variants *blur* and *transparency*, however, have not been rated as intuitive by the majority of participants. This observation is to some extent similar in the *suitability* plot. However, there are some distinct differences observable between the rated intuitiveness and suitability for some of the variants. Although being rated as relatively intuitive, the variant *pattern* is rated as not suitable by the majority of participants. A similar observation can be made for the scribble variant, which has primarily been rated as not suitable, while being perceived as intuitive by most participants. Similarly, the variant *blur* has been clearly rated as not suitable by most of the participants, while the already low rating for intuitiveness has been comparatively less clear. In general, it is observable that for all design variants there is a shift towards lower suitability as compared to the intuitiveness rating. This shift becomes apparent when comparing the mean rating values as provided in Table 6.1. For calculating these values, the ratings have been coded as follows (the same applies for the suitability scale): 1 = *very unintuitive*, 2 = *rather unintuitive*, 3 = *rather intuitive*, 4 = *very intuitive*. Thus, a higher value refers to a higher agreement to the visualization being intuitive or suitable. Consequently, the mean values for *suitability* are lower than the values for *intuitiveness* for all design variants.

Table 6.1: Mean rating values for intuitiveness and suitability, and Spearman correlation statistics.

Design variant	Intuitiveness		Suitability		Spearman's ρ	p-value
	M	*SD*	*M*	*SD*		
Blur	2.23	.81	1.69	.72	.43*	< .001
Distortion	2.65	.98	2.4	.93	.52*	< .001
Intensity Area	3.23	.81	3.14	.8	.6*	< .001
Intensity Line	3.03	.84	2.98	.81	.55*	< .001
Pattern	2.52	1.04	1.66	.76	.42*	< .001
Scribble	2.68	.73	2.28	.76	.46*	< .001
Transparency	2.09	.85	1.99	.78	.52*	< .001

A Spearman correlation for ordinal data has been performed to examine, if there is a statistical relation between the two variables *intuitiveness* and *suitability*. As visible in Table 6.1, this relation has been found significant for all design variants, which verifies sub-hypothesis *H2*. In all cases, a positive relationship can be observed, which means that for example in case a map has been rated as intuitive, it is likely to be also rated as suitable. The correlation coefficient (Spearman's ρ) reveals that the relation between intuitiveness and suitability has been found strongest for the variants *distortion*, *intensity area*, *intensity line* and *transparency* (Spearman's $\rho > .5$). As expected, this relation is comparatively less strong for the variants *blur, pattern* and *scribble*, with larger differences between the ratings for intuitiveness and suitability.

6.1.5 Results – Attractiveness

The perceived attractiveness of the route map visualizations has been evaluated based on the ranking results. Figure 6.3 shows for each rank (1 – 7) the percentage of how frequently a design variant has been selected for this rank. The bar for rank 1 (highest attractiveness) shows the design variants based on their attractiveness in descending order (from left to right). The bars for rank 2 – 7 use the same order of variants as shown for rank 1. In general, the results for the rated *attractiveness* of the maps are in line with the earlier described results, particularly with those for *suitability*. Thus, the map visualizations rated as most attractive are those using the design variants *intensity area* and *intensity line*, while maps using the variants *pattern* and *blur* are perceived as least attractive.

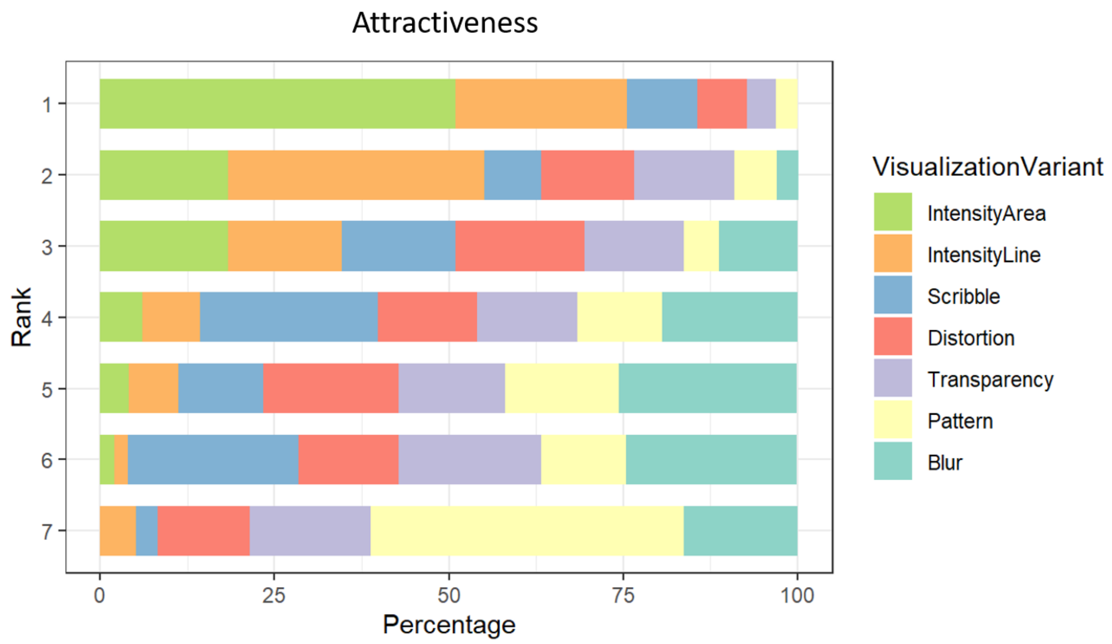


Figure 6.3: Attractiveness rating of the seven different visualization variants of route map designs in percent – visualized separately for each rank (rank 1 = highest attractiveness, rank 7 = lowest attractiveness).

6.1.6 Discussion and conclusion – User study 1

The results of the survey indicate that some of the proposed variants can serve as appropriate design choices for rendering route maps that communicate air quality information.

Figure 6.4 shows a qualitative evaluation of the performance of the seven tested design variants concerning the different tested aspects *attractiveness*, *intuitiveness* and *suitability*. Arrows of different pointing directions and colors indicate how well a variant performed with respect to a tested aspect. It is important to clarify that this evaluation does not represent numerical values, but rather provides a qualitative assessment that should help getting an overview of how the different design variants performed. Similar evaluations using the same type of representation are also provided for user study 2 (chapter 6.2.10) and user study 3 (chapter 6.3.8).

Variant	Attractiveness	Intuitiveness	Suitability
Blur	↓	↘	↓
Distortion	→	→	→
IntensityArea	↑	↑	↑
IntensityLine	↗	↗	↗
Pattern	↓	→	↓
Scribble	→	↗	↘
Transparency	→	↘	↘

↑ Very good ↗ Rather good → Neutral ↘ Rather poor ↓ Very poor

Figure 6.4: Qualitative evaluation of the performance of the proposed design variants concerning different tested aspects.

While some of the tested variants, such as *intensity area* and *intensity line* seem to be appropriate representations based on all three scales *intuitiveness*, *suitability* and *attractiveness*, other design variants such as *blur* or *transparency* do not seem to be appropriate design choices. The tendency of area-type visualizations being generally evaluated more positive in terms of intuitiveness, suitability and attractiveness for visually communicating air quality, partly verifies sub-hypothesis *H1*; with an exception of the line-based variant *intensity line* also being evaluated as positive. Interestingly, the symbology presented with the design variant *pattern* has been rated as somewhat intuitive, while it has not been found attractive or suitable for communicating pollution information. This result might be directly related to the skull icon used for creating the pattern, which (in many cultures) is a very explicit and potentially emotive icon for representing hazards or contaminations. Hence, this map visualization may have a rather deterrent effect on the viewer. A potential effectiveness of this type of map on influencing route choice due to emotional responses to the map design is investigated in a follow-up study described in chapter 6.3. Since the design variant *pattern* uses specific, scenario-related icons, it is possible that results may differ when considering a different icon choice. In general, it seems that design variants using a relatively simple symbology with variations in intensity value of color are preferred over more complex visualizations, possibly combining several visual variables. One reason for this preference might be that these types of symbologies are best known by map users and therefore relatively easy to decode.

The findings of the user survey validate the intuitiveness of most of the proposed map representations, while visual attractiveness and suitability for communicating pollution information seems to be limited to less complex visualizations that primarily use variations in color.

6.2 User study 2: Objective usability – Effectiveness of line objects for influencing route choice in the traffic scenario

While the previously presented user study focused on validating the proposed design variants of route maps based on criteria for subjective usability, the following two user studies (user study 2, adapted from Fuest et al., 2021, and user study 3, adapted from Fuest et al., 2023b) primarily investigate the effectiveness of the proposed visualization concepts in terms of objective usability. The aim of both studies is to investigate the effectiveness of different types of cartographic symbolization for nudging a traveler's route choice towards a route that is favorable from a societal point of view. Effectiveness is measured by how many users change their route choice in favor of the longer, but *societally favorable* route after seeing visually modified route map visualizations. The approach that is applied for addressing this problem is to use cartographic symbolization for communicating favorable, as well as non-favorable route options to the traveler. In both studies, the objective usability of proposed design variants is evaluated, by exemplarily addressing the case of recommending a longer, but *societally favorable* route to the map-reader using cartographic symbolization. While in user study 2, a less congested route is recommended (*traffic* scenario), user study 3 compares the effectiveness of the recommendation of a less congested route to the recommendation of a less polluted route (*air quality* scenario). The recommended, *societally favorable* route is not necessarily the faster one, but rather the route, which contributes best to a more even distribution of traffic or emissions; and therefore benefits the whole traffic system. In both studies, a set of design variants is compared, which use different cartographic visualization methods, regarding their effectiveness for visually recommending *societally favorable* routes – using traffic density (user study 2 and 3) or particulate matter pollution (user study 3) as a criterion to communicate routes to be preferred or to be avoided. The recommendation of route options using different cartographic design variants is expected to affect route choice behavior. Hence, the map-reader is expected to intuitively decide for the route that is visually communicated as *societally favorable*.

In the following, the methodology applied for user study 2 is described. Since the design specifications of both user study 2 and user study 3 are to some extent overlapping, first, the main similarities in the design of both user studies are summarized in the following sub-chapter, while further similarities are specified later at the respective position in the text.

6.2.1 Common design specifications in user study 2 and user study 3

To ensure comparability among the different user studies, the following design specifications that have been introduced for user study 2, were also applied for user study 3.

For creating route maps, several different urban road structures within German cities were used. Since most of the larger German cities include historically grown, unique urban structures, differences in the general layout of a city are considered. This larger variety of study areas intends to reduce the influence of familiarity with a city's road network. Additionally, based on the study design, the aim is to direct the focus to the comparison of the proposed routes, rather than the fact that different visualization techniques have been applied.

Each of the route maps includes a pair of two route options (A and B), which do not intersect each other and both routes share the same start- and end-points. Those route pairs always consist of one non-favorable route and one slightly longer route that is favorable based on the current traffic situation or air quality conditions. For representing the two route options, A and B, a solid blue line is used (except for design variants that used variations in color hue). The start and end point of the routes are marked by distinctive icons. The car icon represents the start of the route, while the pin icon indicates the end of the route. A background map is used for providing a general spatial orientation to the map-reader. To facilitate map-reading, familiar visualization of map background information (such as land use or additional roads) is used, as commonly applied in routing services.

In all cases, the shorter, non-favorable route ranges between 80 % and 90 % of the length of the longer, favorable route. In particular, larger differences in length between the two routes have been avoided, since with long detours, the emissions of cars also add a considerable amount of further pollution to the atmosphere, which would contradict the concept of promoting *societally favorable* routes.

Route pairs were used to generate both *non-modified* maps, where both routes were depicted using the same map symbols without visual variations, and *modified* maps, where different symbols were applied to visually communicate favorable and non-favorable routes. In both user studies, each half of the maps were non-modified maps, since for each modified map, there was a neutral, non-modified version showing the same map section as a baseline representation. Since the *non-modified* map does not show any visual modification between the routes, and no further information was provided, participants are expected to choose the slightly shorter route when working with these maps. The symbolization applied to the modified route maps intends to nudge the map-reader to choose the longer route that is visually communicated as more favorable.

To construct the *modified* maps, the graphical differences in the map symbols that indicated varying levels of traffic congestion or air quality along the routes were generated from an input data set, while for all route maps, both route options differ clearly regarding the visual communication of their favorability.

6.2.2 Sub-hypotheses

Prior to conducting the experiment, four sub-hypotheses have been developed, which are derived from the key hypotheses introduced in chapter 1.2, and verified as part of the following analysis.

H1:
"Map symbolization is expected to be effective for influencing route choice; demonstrated by a general shift towards choosing the longer, but *societally favorable* route when showing the modified maps as compared to route choice for non-modified maps." (Derived from *Hypothesis 1*)

H2:
"Map symbols are expected to be more effective, when graphical differences between the representation of favorable and non-favorable routes are stronger." (Derived from *Hypothesis 1*)

H3:

"Map readers are expected to need less time for route choice decision making when viewing route maps using map symbolization." (Derived from *Hypothesis 1*)

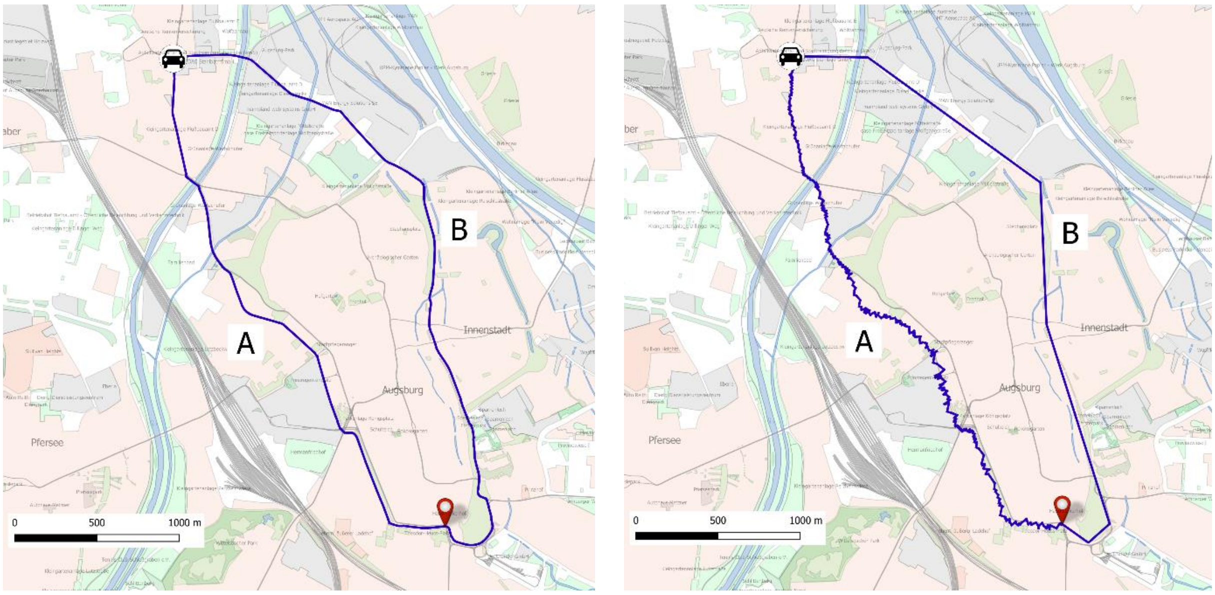
H4:

"The willingness to choose the favorable route is expected to depend on the characteristics, participants associate with a representation." (Derived from *Hypothesis 2*)

6.2.3 Route maps

User study 2 investigates the effectiveness of different types of cartographic design variants for influencing route choice, by visually modifying line objects that represent routes in a route map. The study specifically tests the *traffic* scenario, which means that the route visualizations should indicate traffic congestions. Among other higher-level reasons, such as reducing air pollution or fuel consumption, congestion reduction is central to maintaining an efficient and safe transport system.

A set of 36 route maps (18 modified and 18 non-modified) of areas within 18 different German major cities of comparable size has been created. In this study, a *routing scenario* is denoted as the pair of a *non-modified* and the corresponding *modified* map for the same study area. An example of both types of maps is provided in Figure 6.5.



1 2

Figure 6.5: Example of a non-modified map (1) and a corresponding modified map of the same area using distortion with strong intensity (2). Route A is slightly shorter than Route B. Map data from OpenStreetMap.

Each of the 18 *modified* maps represents the same routing scenario as the corresponding non-modified map by modifying the visualization using different design variants. Hence, for each city, there is a *non-modified* map and a *modified* map of the same area using one of the cartographic design variants. The modification aims to prefer one route to the other using different cartographic design variants.

In the experiment, the focus is on a morning-rush-hour scenario, in which the shorter route is affected by a temporary disturbance in terms of traffic jam – resulting in the longer route to be the preferable choice for achieving system-wide traffic efficiency. While the different design variants visualize this temporary change in traffic density in different ways, the temporarily favorable route is always aimed to be recommended as a result of the modification.

6.2.4 Design variants

For communicating the traffic-related information to the map-reader, six different design variants of route maps are compared exemplarily, using variations in: a) *color hue*, b) *spacing*, c) *size*, d) graphical *symbols*, e) *length distortion*, and f) shape distortion *(distortion)*. In order to investigate, how strong the graphical differences for symbolizing favorable and non-favorable parts of a route need to be applied in order to achieve a behavior change, the six design variants are prepared in three different levels of intensity (described in detail below in chapter 6.2.5); in total, resulting in 18 modified maps.

In the following, a detailed description of the design characteristics of the six different variants for visualizing route favorability is provided.

Color hue

Among all tested design variants, *color hue* is the most frequently applied type of symbolization in route maps. It colors route segments based on the traffic light metaphor: Favorable route segments are displayed in a green hue, while non-favorable segments are shown in a red hue. Route segments with observed values that equal the threshold are visualized in yellow. This variant is also used with the same specifications in user study 3 (variant *Color line*, chapter 6.3.3.1).

Spacing

The *spacing* variant uses dashed lines (geometric symbols) for communicating route favorability. Short gaps between dashes represent low traffic density, while long gaps symbolize high traffic density and low favorability.

Size

The *size* variant varies the line size of routes. In accordance with previous findings (Carroll at al., 2020), non-favorable route segments with observed values that exceed the threshold are visualized as increasingly narrow, while favorable route segments are symbolized with wider lines. This type of visualization should present the route as a bottleneck with increased traffic volume.

Symbols

The *symbols* variant uses a linear arrangement of symbols (in this case car icons) for representing favorability of routes. Favorable parts of the route are represented by a larger amount of symbols than non-favorable parts of the route. This variant is similar to the *Icons line* variant introduced in user study 3 (chapter 6.3.3.1). However, in that study, the symbol choice is changed to arrows for favorable segments and cross symbols for non-favorable segments, while favorability is indicated by the symbol size.

Length distortion

The variant *length distortion* adapts the geometry of route segments in a way that favorable parts of the routes are visualized as shorter as they are in reality, while non-favorable parts are represented as longer – according to the generalization technique introduced in chapter 5.3.2.

Distortion

The *distortion* variant is proposed as an alternative way of visualizing route favorability (see chapter 5.3.1) and is based on cartographic generalization techniques (Fuest & Sester, 2019). Non-favorable route segments exceeding the threshold are visualized by an increasing degree of distortion. The impression of distortion is achieved by adding points (randomly on the left or the right side of the route) a specific distance away from the original line. Favorable route segments, however, are increasingly simplified based on the Douglas-Peucker-Algorithm for line simplification. This variant is also used with the same specifications as the variant *Distortion* in user study 3 (chapter 6.3.3.1).

While the first four design variants use common types of map symbols, the design variants *length distortion* and *distortion* have been developed as new approaches for communicating route information, using cartographic generalization techniques (Fuest & Sester, 2019).

The six proposed design variants are informationally equivalent, which means that they visualize the same traffic density information associated with the routes (Fabrikant et al., 2010). However, for each design variant, the visual characteristics for representing temporarily favorable (low traffic density) or non-favorable (high traffic density) route options differ. Table 6.2 summarizes the visual metaphors for communicating low and high traffic densities for the six different design variants.

Table 6.2: Visual metaphors for communicating traffic densities using different design variants.

Design variant	Visual metaphor	
	Low traffic density	*High traffic density*
color hue	Green color hue	Red color hue
spacing	Short gaps between dashes	Long gaps between dashes
size	Wide line (much capacity)	Narrow line (little capacity)
symbols	Small amount (car symbols)	Large amount (car symbols)
length distortion	Visually shorter route	Visually longer route
distortion	Simplified line	More complex (distorted) line

Although the original geometry has been modified for some of the design variants, for all map representations, the topological relations between map elements are retained. Figure 6.6 shows the map representations of all design variants, using *strong* intensities of modification. For all map representations, Route B is recommended as the temporarily more advisable route option. The full set of modified and non-modified maps prepared for this study is provided in the Appendix of this thesis (Figures A.1 – A.6).

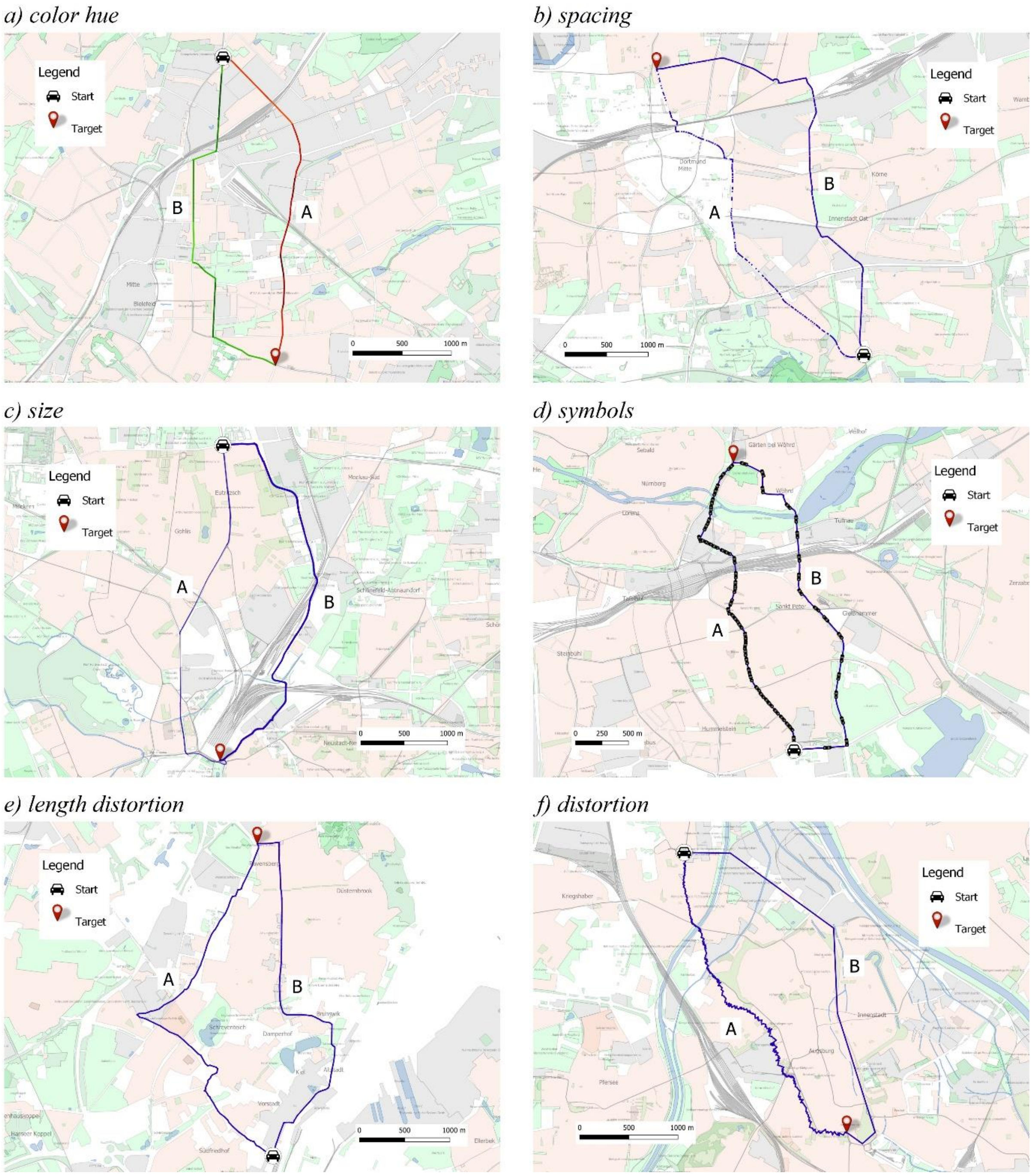


Figure 6.6: Sample maps showing the six different design variants, as applied to route visualization. a) color hue, b) spacing, c) size, d) symbols, e) length distortion, f) distortion. Map data from OpenStreetMap.

While *color* as a visual variable is commonly classified into the different dimensions “hue”, “lightness” and “saturation”, it was decided to only test *color hue* using a red-green color scale as a design variant, since this type of color scale is very commonly and frequently used for communicating traffic in some of the prevalent routing services.

6.2.5 Calculation of graphical differences among design variants and modification intensities

In this study, traffic density is used as a factor, which serves as a basis for visually communicating route recommendations – represented by visual variations. The visualizations are automatically created based on the traffic density associated with road segments.

For all routing scenarios in the 18 different cities, the same distribution pattern of traffic density is simulated. For that, the two routes A and B are divided into logical sub-sections (primarily split at important intersections along the route), while allowing variability in length due to differences in the road network structure. For further calculations, the factor *r* (see equation Eq. 4.3 in chapter 4.3.2) is used, while taking the actual measured traffic density as observed values and the long-term average traffic density of a road segment as the threshold between an acceptable and an unacceptable traffic volume.

Figure 6.7 shows the distribution pattern of the traffic density ratio on a sample pair of routes from the study. All road segments from the left route relate to non-favorable route segments with a high traffic density ($r > 1$), whereas the segments from the right route correspond to favorable route segments, with a low traffic density ($r < 1$).

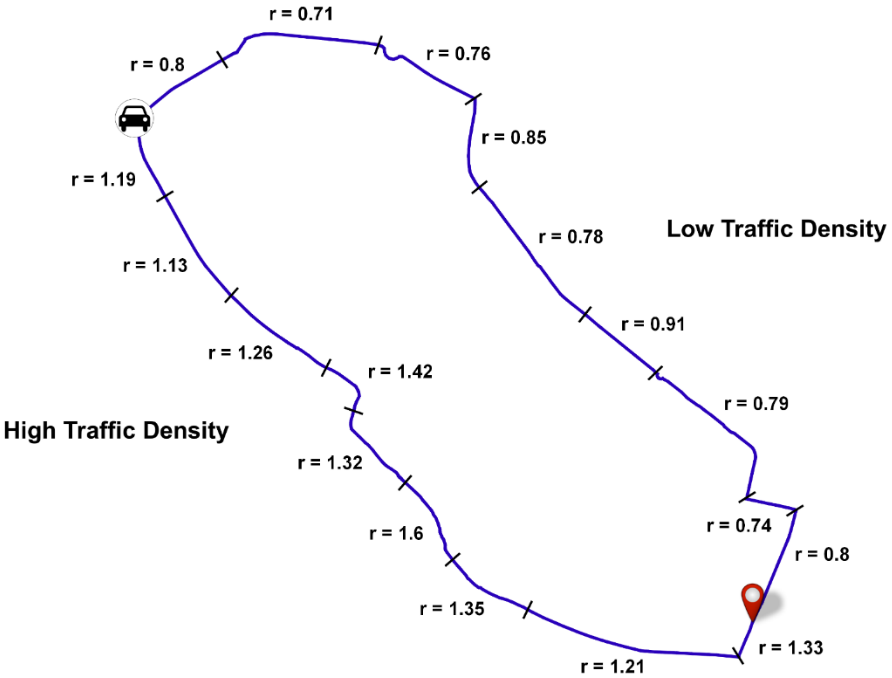


Figure 6.7: Distribution pattern of the factor r as used for the user study.

The factors used for the different visualizations all depend on the value *r* and additionally on a weight *w* when using a modification intensity that deviates from the *medium* intensity. The parameters for appropriately calculating the factors have been derived by first determining the visual characteristics for each design variant, which should be varied depending on the traffic density; and subsequently performing visual experiments for determining an appropriate value range.

To determine a suitable way for visualizing traffic information for influencing route choice, the effectiveness of three levels of intensity for the visualization is compared: 1) *weak* (expected lower boundary), 2) *medium* and 3) *strong* (expected upper boundary). Each design variant is represented once using each level of intensity.

For the *medium* intensity, the visualizations are always based on the original traffic density distributions, indicating an objectively perceived, appropriate representation of the traffic-related information. While the *weak* intensity of modification reduces the visualized differences in traffic density distributions to provide a more subtle representation of the information, the *strong* intensity increases these differences towards a more protruding representation. Importantly, these three tested levels of intensity for modification could be extended by an infinite number of intensities between them.

Table 6.3 provides details regarding the graphical differences concerning the different intensity levels for modifying the maps. As an example, it is specified how three different values for factor *r* affect the calculation and representation of the visual characteristics of each design variant. In particular, for this study, the calculation of visual characteristics has been adapted to a limited value range: $0 \leq r \leq 2$, assuming $r = 2$ as the ratio of the maximum observed value and the threshold.

Table 6.3: Graphical differences (values for variation) between the six design variants among the intensity levels medium, weak, and strong.

Design variant		Intensity		
	Factor *r*	***weak***	***medium***	***strong***
color hue	0.5	green - yellow	green	dark green
Variation: Color hue (hex code)	1	yellow	yellow	yellow
	1.5	orange	red	dark red
spacing	0.5	0.75	0.5	0.25
Dash length = 1 mm (fixed)	1	1	1	1
Variation: Length of blank space between dashes (mm)	1.5	1.25	1.5	1.75
size	0.5	1	1.2	1.4
Variation: Width of line (mm)	1	0.8	0.8	0.8
	1.5	0.6	0.4	0.2
symbols	0.5	1 / 125	1 / 150	1 / 175
Variation: Number of symbols to place on the line (symbols/meters)	1	1 / 100	1 / 100	1 / 100
	1.5	1 / 75	1 / 50	1 / 25
length distortion	0.5	0.75	0.5	0.25
Variation: *enlarge* factor for scaling objects	1	1	1	1
	1.5	1.25	1.5	1.75
distortion	0.5	5	10	15
$r < 1$: Removing points from line (line simplification)	1		no change	
Variation: Threshold for simplification (*epsilon*) in meters	1.5	5	10	15
$r > 1$: Adding points to line (line distortion)				
Variation: Distance (*d*) between line and new point in meters				

Figure 6.8 depicts the graphical differences between the three different levels of intensity for modification using a sample pair of routes for the design variants *symbols*. Route B indicates the *societally favorable* route.

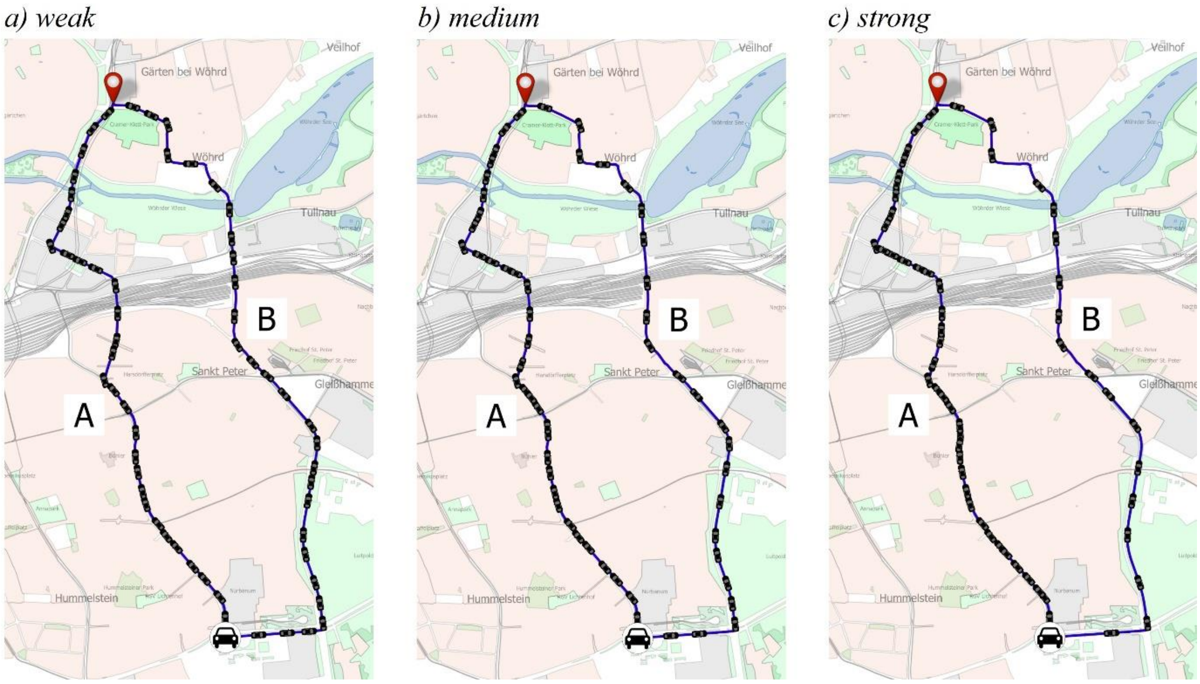


Figure 6.8: Comparison of the graphical differences between the three levels of intensity (design variant symbols): The ratio of the number of car symbols between both routes varies depending on the intensity of modification. Levels of intensity: a) weak, b) medium, c) strong. Map data from OpenStreetMap.

6.2.6 Study design

The user study has been designed as an online experiment using a within-subjects design. An overview of the study design is provided in Figure 6.9.

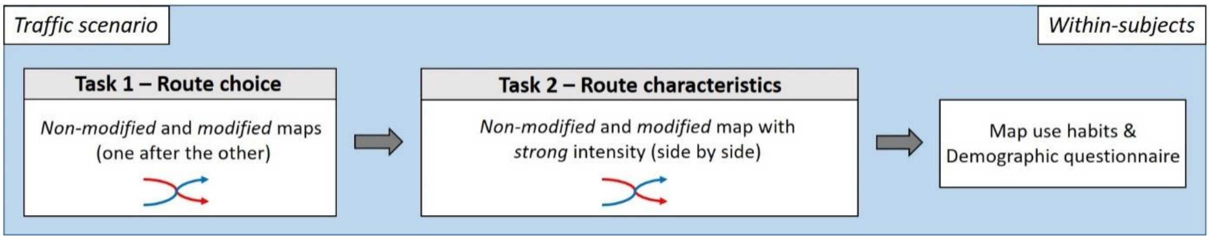


Figure 6.9: Study design of user study 2.

In the first set of tasks, each participant made a route choice decision for each map right after shortly observing it, whereas the time for viewing each map has not been limited. Maps were shown – one after the other – in a randomized order. The task was prepared in the same way as the route choice task, which is part of user study 3 (chapter 6.3). In both user studies, participants were asked to select their preferred option based on a 5-point Likert scale (options placed below each map, example provided in Figure 6.10). The options were *Definitely A*, *Rather A*, *No preference*, *Rather B*, or *Definitely B*. That is to not only obtain a route decision in a "yes/no" format but also to obtain information on the degree of approval or disapproval regarding the routes. The "no preference" option was provided in order to offer a high level of freedom of choice to the participants during route choice decision making. Option A always referred to the route visualized on the left, option B to the route visualized on the right. To make less obvious, which side is showing the favorable route, and thus to avoid potential biases, in user study 2, in 11 of the cases, the longer, but *societally favorable* route was denoted as "Route B", in seven cases as "Route A". The resulting values were recoded during analysis so that a higher value for route choice always relates to choosing the favorable route in the *modified* maps (1 = Definitely non-favorable route, 2 = Rather non-favorable route, 3 = No preference, 4 = Rather favorable route, 5 = Definitely favorable route). Maps were presented in full-screen size to ensure better visibility of details.

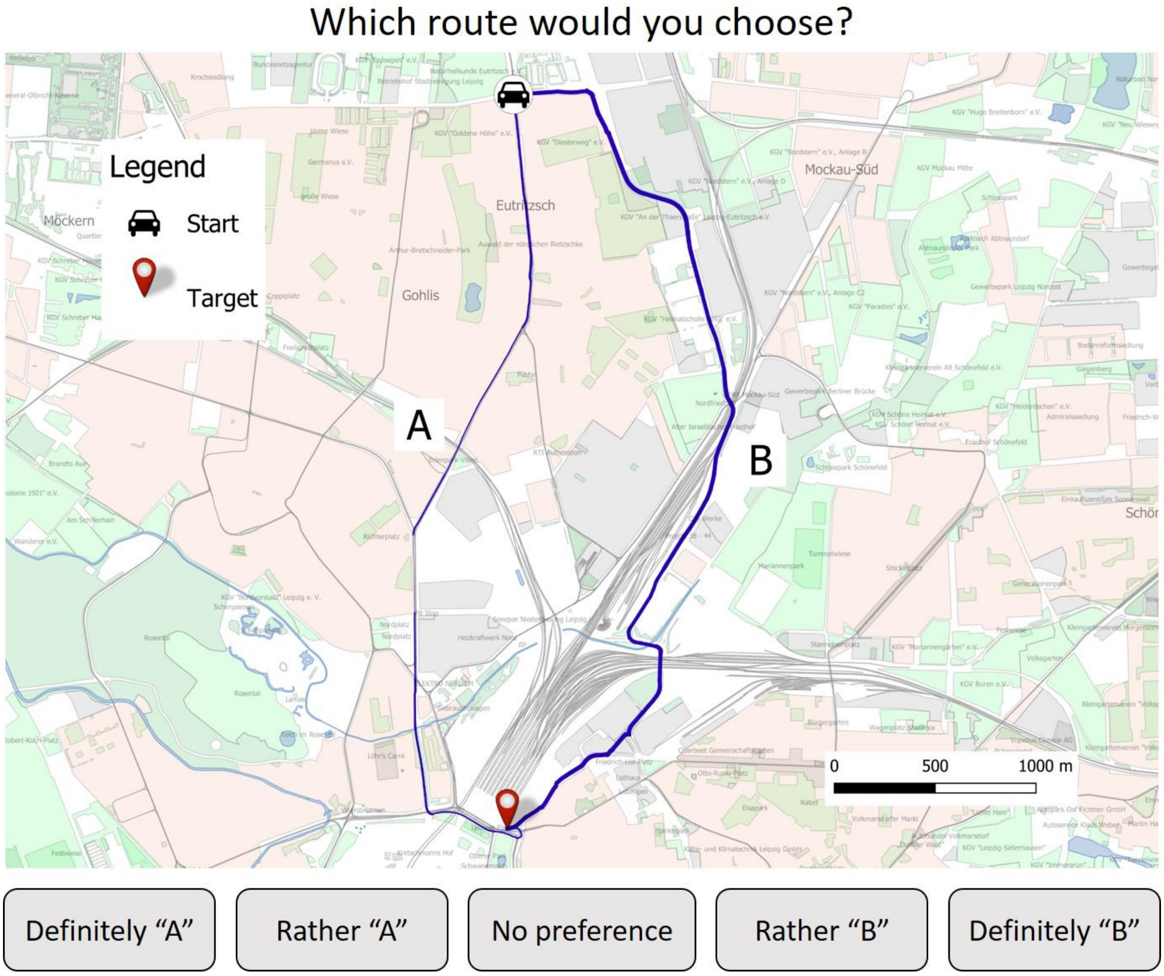


Figure 6.10: Example of a route choice task as prepared for user study 2 and user study 3. Likert scale options for route "A" are placed below the map on the left side, options for route "B" on the right side, corresponding to the position of the routes in the map. Participants needed to choose one of the options, in order to be able to continue with the experiment. Map data from OpenStreetMap.

For the next set of tasks, participants have been presented the *non-modified* and the *modified* visualization for the same routing scenario side by side – and were asked to name characteristics of the visually modified routes. This task has been prepared once for the six different design variants (presenting the version using the *strong* intensity of modification) and displayed in random order for each participant. The task was defined as follows: "As you see, we have modified the routes. How has the relationship between the routes changed? Route A [or B] now appears to be …" A checklist of six options regarding the characteristics of the route (*faster*, *more direct*, *shorter*, *more comfortable* to drive, *more fluent* to drive or *none of this*) as well as an option of adding a description to a free text box followed these instructions. The participants were asked to select at least one of the options, however, multiple responses were also allowed.

After completing the tasks, the participants were asked to assess their map use habits and experiences. In particular, they were asked to assign themselves to one of the following five categories (coding scheme in parentheses), as described in Lai and Yeh (2004): "Competent" (0), "comfortable" (1), "occasional" (2) or "inexperienced" (3) map users, as well as "outsiders" (4), who "have not used a map on [their] own" (p. 231). In the experiment task, participants only saw a one-sentence statement for each category, describing the level of expertise in map usage. The experiment concluded with a questionnaire on demographic information with a focus on the driving experience.

6.2.7 Participants

In total, 151 participants completed the study (80 females, 70 males, 1 diverse). The participants range in age from 18 to 57 years (M = 26.20, SD = 6.49). Participants were recruited by inviting students and staff members of different institutes at the authors' universities, as well as persons from various non-scientific backgrounds, to obtain a more diverse sample than would typically be achieved by studying only university students. Since the study has been prepared in German language, all participants were German residents.

In terms of driving experience, 91.4 % of all participants indicated that they own a driver's license, while on average they received the license 9.1 years ago (SD = 6.39). Furthermore, participants report that they drive on average 5199.15 kilometers per year (SD = 6481. 58), ranging from 0 to 30000 kilometers per year. 96.7 % of the test persons had no visual impairment, 46.4 % of them using a visual aid.

6.2.8 Results – User study 2

The results of this user study were analyzed regarding the effectiveness of the six different proposed design variants for visually communicating *societally favorable* routes, measured by the fact that participants made a change in their route choice decision.

In the following, the temporarily favorable route is always referred to as the recommended, *societally favorable route* in the *modified* representations. The results for route choice did not always follow a normal distribution, particularly for the *modified* visualizations. That is because generally very few participants chose the *no preference* option located in the middle of the rating scale, but rather decided for one of the two route options.

6.2.8.1 Influencing route choice

At first, it is observed for each of the design variants how the route choices made for both the *non-modified* scenario as well as for the *modified* scenario differ. Table 6.4 shows the differences in mean values for route choice for the individual design variants between the *non-modified (n.-mod.)* visualization and the *modified (mod.)* visualization of the same routing scenario.

*Table 6.4: Mean values for route choice between the groups non-modified (n.-mod.) and modified (mod.) and statistics for the Wilcoxon test results (z-score and p), n = 151, *p < .05. Wilcoxon effect size (r) (Cohen, 1988):* ***small effect****: 0.1 ≤ r < 0.3;* ***medium effect****: 0.3 ≤ r < 0.5;* ***large effect****: r ≥ 0.5.*

Design variant	Intensity														
	weak					medium					strong				
	n.-mod.	*mod.*	*z*	*p*	*r*	*n.-mod.*	*mod.*	*z*	*p*	*r*	*n.-mod.*	*mod.*	*z*	*p*	*r*
color hue	2.03	2.97	-7.4	.0*	.43	2.6	3.11	-4.22	.0*	.24	2.16	2.91	-6.08	.0*	.35
distortion	3.87	4.03	-1.96	.05	.11	3.29	3.71	-3.88	.0*	.22	2.15	3.8	-8.86	.0*	.51
length distortion	2.95	3.52	-4.7	.0*	.27	1.97	3.71	-9.71	.0*	.56	1.81	3.66	-10.13	.0*	.58
spacing	3.30	3.23	-0.92	.36	.05	1.82	2.25	-4.09	.0*	.24	2.66	3.22	-4.52	.0*	.26
size	3.38	3.42	-0.38	.7	.02	2.42	2.56	-1.64	.1	.09	1.98	2.28	-3.61	.0*	.21
symbols	2.77	3.34	-4.96	.0*	.29	2.6	3.62	-7.05	.0*	.41	2.59	4.11	-9.2	.0*	.53

In general, it can be observed that for the majority of routing scenarios there is a shift from choosing the shorter route in the *non-modified* maps (lower mean values), towards choosing the longer, but *societally favorable* route in the *modified* visualizations (higher mean values), indicating that the modification of route visualizations does actually lead to a different route choice behavior.

Using a Wilcoxon signed-rank test for non-parametric data, the difference between the route choices made for the *non-modified* and the *modified* visualization has been found significant for most of the routing scenarios (see Table 6.4), except for *distortion* with *weak* intensity, *size* with *weak* intensity, *size* with *medium* intensity and *spacing* with *weak* intensity. These results indicate that for 14 out of the 18 routing scenarios, the applied visual modifications have a significant effect on route choice behavior (in favor of the *societally favorable* route), which verifies sub-hypothesis *H1*. In particular, four of the scenarios (*distortion* with *strong intensity*, *length distortion* with *medium* and *strong* intensity, and *symbols* with *strong intensity*) evoke a large effect for influencing the map-reader's route choice based on the applied visual modifications. The larger the effect, the more likely the map-reader would choose the *favorable* route.

For further analysis, the differences between the values describing the route choices for the *modified* visualizations and the corresponding *non-modified* visualizations have been calculated as a new variable, by subtracting the values for the *non-modified* visualizations from those for the *modified* visualizations. This variable differs from the previously described *route choice* variable (categorical), since it is a metric variable describing the *change* between the route decision made for the *non-modified* map and the *modified* map of the same routing scenario. The analysis of this calculated variable also intends to reduce influences caused by some road-network based factors (between the different routing scenarios), which may lead to route choices being always more in favor of the *recommended* or the *non-recommended* route. These *difference* values indicate to which extent the participants changed their route choices in favor of the longer, but *societally favorable* route when presenting the *modified* visualizations. It is suggested that the values for this *difference* serve as an indicator for the effect of visualization on route choice behavior – more specifically the willingness to decide for the *favorable* route.

Figure 6.11 shows for each of the six design variants the mean values of the *difference* variable including error bars for the *standard error*. The visualization illustrates how the willingness to decide for the *favorable* route varies based on the intensity of modification in the visualization. For most of the design variants, an increase can be observed, indicating that participants were more willing to decide for the *favorable* route if the routes have been visualized using a higher intensity of modification – verifying sub-hypothesis *H2*. An exception, however, is the design variant *color hue*, for which the *weak* intensity seems most effective. While design variants like *length distortion* or using *symbols* generally seem to influence route choice behavior at different levels of modification intensity, other variants like *size* or *spacing* only have a weak effect on the participants' route decisions. In the case of modifying the routes using *spacing* with *weak* intensity, the route decisions are on average even slightly more in favor of the *non-favorable* route (negative *difference* value).

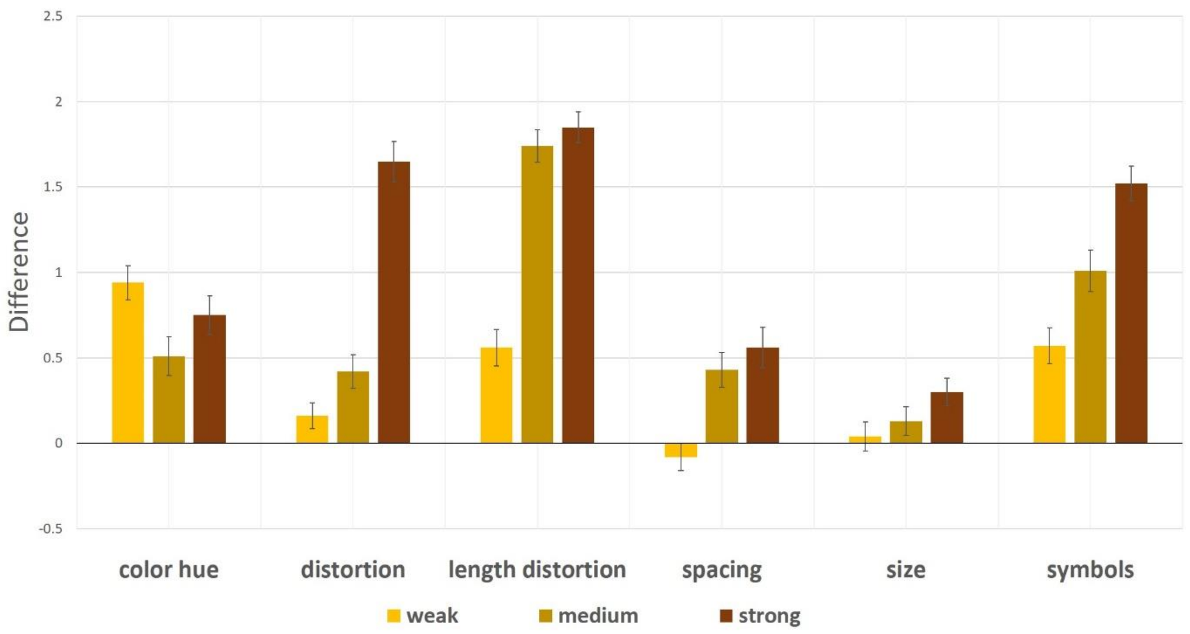


Figure 6.11: Willingness to decide for the societally favorable route, difference values can range from -4 to 4, n = 151.

To investigate the influence of the type of design variant, the intensity of modification, as well as the interaction of both factors, on route choice behavior, a repeated-measures ANOVA was performed. Results reveal a significant main effect for the type of design variant, $F_{(5,\ 750)} = 50.87$, $p < .001$, $\eta^2 = 0.253$. Similarly, the differences between the three levels of intensity for modifying the visualizations has been found significant: $F_{(2,\ 300)} = 101.16$, $p < .001$, $\eta^2 = 0.403$. Using a Greenhouse-Geisser correction (due to lack of sphericity in the repeated-measures ANOVA), furthermore a significant interaction effect has been found, indicating that for the different design variants, route choice behavior differs depending on the level of intensity of modification, $F_{(9.06,\ 1358.54)} = 19.13$, $p < .001$, $\eta^2 = 0.113$. A post-hoc t-test using a Bonferroni correction further emphasizes a different influence of the six design variants on route choice. Table 6.5 shows that for all pairs of design variants except *color hue* and *distortion*, as well as *spacing* and *size*, the willingness to decide for the *societally favorable* route differs significantly ($p < .05$, marked bold).

Table 6.5: Pairwise comparison (Post-hoc t-test) between the six different design variants, n = 151, $^*p < .05$.

Design variant	*color hue*		*distortion*		*length distortion*		*spacing*		*size*		*symbols*	
	t	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*	*t*	*p*
color hue	-	-	-.09	.93	-6.89	**.0***	4.45	**.0***	6.31	**.0***	-2.95	**.0***
distortion	-.09	.93	-	-	-7.58	**.0***	5.29	**.0***	-7.31	**.0***	-3.18	**.0***
length distortion	-6.89	**.0***	-7.58	**.0***	-	-	-12.63	**.0***	-15.53	**.0***	3.51	**.0***
spacing	4.45	**.0***	5.29	**.0***	-12.63	**.0***	-	-	-1.9	.06	-8	**.0***
size	6.31	**.0***	-7.31	**.0***	-15.53	**.0***	-1.9	.06	-	-	-9.74	**.0***
symbols	-2.95	**.0***	-3.18	**.0***	3.51	**.0***	-8	**.0***	-9.74	**.0***	-	-

6.2.8.2 Decision time

The time (in seconds) it took the participants to make each of their decisions, has been measured in addition to investigating participants' route choice preferences. Due to the experimental setup, it was not possible to monitor the participants' activities during the experiment. A small number of extreme values was found that are most likely the result of external disruptions or longer interruptions of the experimental procedure by the participant. These arbitrary interruptions are not necessarily related to the concerned route choice scenario. Extreme values larger than 60 (seconds) for a route decision have been defined as outliers and were excluded from further analysis. On average this applies to 3.9 % of all cases for the different routing scenarios.

For investigating the relationship between the time needed to decide for a route when viewing either the *non-modified* or the *modified* visualization of the same routing scenario, paired t-tests were conducted. These tests (see Table 6.6) revealed that for six of the 18 routing scenarios, participants needed significantly more time when viewing a modified visualization ($p < .05$, marked bold). In four of these cases, this applies to the *strong* intensity of modification. This observation is particularly interesting, since based on sub-hypothesis *H3*, symbolization was expected to help the viewer making a faster route choice decision.

Table 6.6: Mean values (time in seconds) for the non-modified (n.-mod.) and modified (mod.) visualizations and t-test results, n =138, * p < .05.

Design variant	Intensity											
	weak				*medium*				*strong*			
	n.-mod.	*mod.*	*t*	*p*	*n.-mod.*	*mod.*	*t*	*p*	*n.-mod.*	*mod.*	*t*	*p*
color hue	11.97	13.84	-2.29	**.02***	13.59	15.17	-1.39	.17	12.04	15.03	- 3.21	**.0***
distortion	14.54	13.42	.94	.35	13.91	13.42	.82	.41	12.48	14.47	-2.27	**.03***
length distortion	14.19	14.6	-.39	.7	14.48	15.93	-1.94	.05	12.39	15.15	-3.57	**.0***
spacing	12.54	14.41	-1.84	.07	11.01	13.69	-4.13	**.0***	13.25	15.08	-1.9	.06
size	12.76	12.71	-.12	.91	14.39	14.20	-.1	.92	13.15	15	-2.11	**.04***
symbols	13.34	13.55	-.67	.5	13.17	14.24	-1.65	.1	13.42	14.43	-1.28	.2

Similar to the previously described analysis on route choice, furthermore, the difference between the time needed to make the decision when viewing the *non-modified* and the *modified* visualizations, has been calculated – by subtracting the time values of the non-modified visualizations from those of the modified visualizations. This difference indicates the influence of modification on the time needed to make the decision.

Figure 6.12 shows for each routing scenario the mean value of the difference between the times needed for the route decision (including error bars for the *standard error*) when using the *non-modified* or the *modified* map. The illustration further clarifies that for most of the routing scenarios participants needed more time for making their decision when viewing a modified visualization (positive difference value).

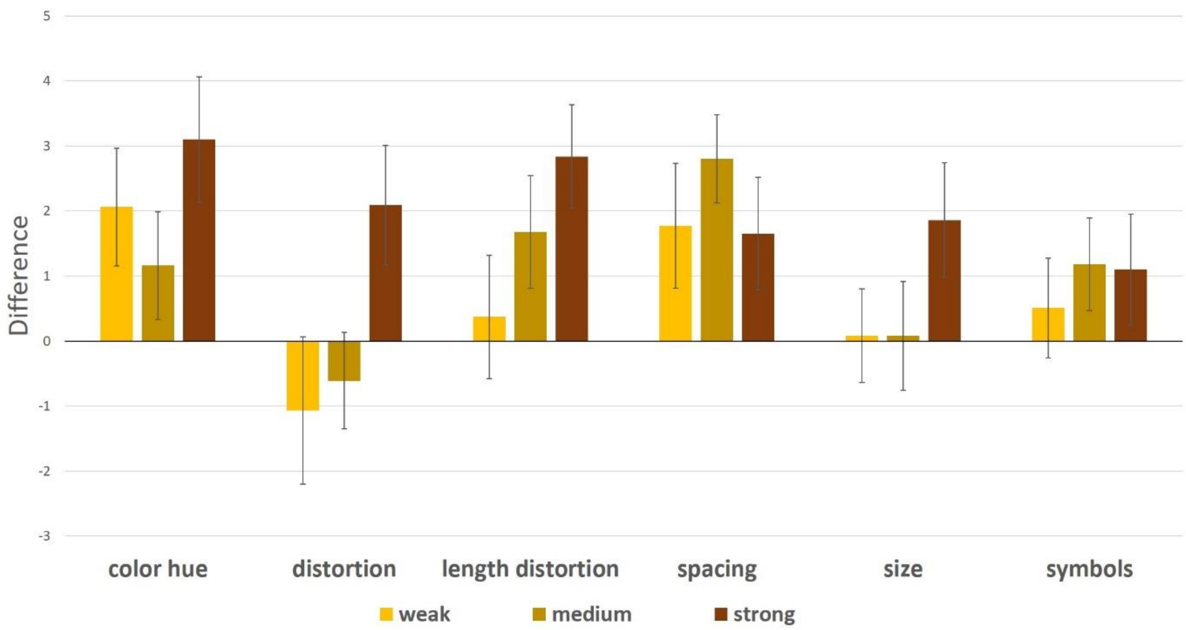


Figure 6.12: Decision time for route choice: Difference (in seconds) between non-modified and modified, n = 138.

A repeated-measures ANOVA was performed to investigate a potential influence of the type of design variant, as well as the intensity of modification, on the time needed to make a route decision. Using a Greenhouse-Geisser correction, results reveal a significant main effect for the intensity of modification, $F_{(1.86,\ 171.21)} = 5.\ 72$, $p < .01$. This indicates that participants needed significantly more time for their route decision (as compared to the corresponding non-modified map) if the map has been modified with a higher intensity. However, for the type of design variant, there was no statistically significant difference, $F_{(4.43,\ 407.48)} = 1.63$, $p = .16$. Regarding the effect size, it was found that according to Cohen (1988), the intensity of modification ($\eta^2 = 0.058$) only has a small effect on the time required for route decisions (see also chapter 2.6.2.6).

To examine a possible relation between route choice and the time needed for making the decision, the difference values for both variables for each of the routing scenarios were correlated. In most cases, the tested relations have not been found significant – indicating that the route choice in favor of the recommended, *societally favorable* route does not depend on the time required for making the decision. For two of the routing scenarios, however, there was a negative correlation: *Distortion* with *strong* intensity ($r = -.22$, $p < .01$) and *color hue* with *strong* intensity ($r = -.212$, $p < .05$). For these two variants, this indicates that participants who were more willing to decide for the *favorable* route in the modified maps, on average needed less time to make their decision. In contrast, participants who were less willing to decide for the *favorable* route took more time for their decisions.

6.2.8.3 Route characteristics

In addition to the results for route choice, the characteristics of the route visualizations, which the participants associate with the different design variants, were analyzed. Although the six different design variants represent the same information about traffic density, the visual variations are assumed to evoke associations with different possible characteristics of the actual route. The associations with the route characteristics are expected to vary among visual variables, due to the use of different visual metaphors.

Table 6.7 summarizes for each design variant the percentage (%) of how many participants associate the different characteristics with the presented route visualization of the *societally favorable* route. For each variant, the characteristic that has the highest percentage has been underlined. Furthermore, all characteristics that have been selected by at least 1/3 of all participants are printed bold. These characteristics can be considered as *important* regarding the visual impression of route maps designed using the specific design variant.

Table 6.7: Estimated route characteristics by the participants in percent (100 % = all participants evaluate the characteristic as applicable), n = 151.

Design variant	Route characteristic						
	faster	*more direct*	*shorter*	*more convenient*	*more fluent*	*none*	*other characteristic*
color hue	**<u>48</u>**	5	4	28	**40**	28	15
distortion	**40**	**38**	17	**<u>57</u>**	**42**	12	8
length distortion	27	**50**	**<u>54</u>**	17	11	14	3
spacing	17	9	2	25	**<u>40</u>**	**<u>40</u>**	10
size	13	6	1	16	18	**<u>60</u>**	15
symbols	**60**	3	4	**42**	**<u>65</u>**	19	9

Routes, which have been visually recommended using the design variant *color hue*, predominantly seem to be *faster*, *more fluent*, or *more convenient* to drive at. Since no geometrical changes were made for this design variant, it makes sense that very few participants judged the routes as being more direct or shorter. Also, a considerable number of participants did not agree with any of the options. This may serve as an indicator, to which extent a visual metaphor has been successfully applied for influencing route choice. For *distortion*, the simplification of the route's geometry for the *societally favorable* route may have led to the driving experience being expected as *more convenient, more direct, faster,* and *more fluent*. Very similar characteristics (except directness) have been associated with the representation using *symbols*. Obviously, for the design variant *length distortion*, the modified routes are associated as being *shorter* and *more direct*, since due to the geometric modifications resulting from this cartographic generalization method, they actually are.

Interestingly, for the visualization, which uses *size* for recommending routes, in most cases, participants decided for the *none of this* option. A similar pattern is observable for the *spacing* variant. This may indicate (together with the results for route choice) that the decoding of the visual metaphor did not work as expected for these design variants; as a consequence their suitability for influencing route choice might be limited.

Furthermore, a relation between the participant's route choice and the estimations regarding route characteristics for the *favorable* route is assumed (sub-hypothesis *H4*), indicating that participants who decided for the *favorable* route, on average rather agreed to the route characteristic; and similarly, participants who decided for the *non-favorable* route rather disagreed to the route characteristic. To investigate this relation, chi-squared tests were performed for the relations between the route choice (*strong* intensity of modification as used for the task) and the participant's estimation regarding route characteristics. In particular, an expected relation may occur, if there are high values for route choice (participant decided for the *favorable* route) and a value '1' for the characteristic (approval for the characteristic); similarly, low values for route choice, in combination with the value '0' (disapproval) for the characteristic.

Figure 6.13 shows a heat map with the Pearson chi-square values for the relations between the six design variants and the route characteristics. Values marked in dark orange indicate a strong relation, whereas values marked in lighter orange indicate a lower relation.

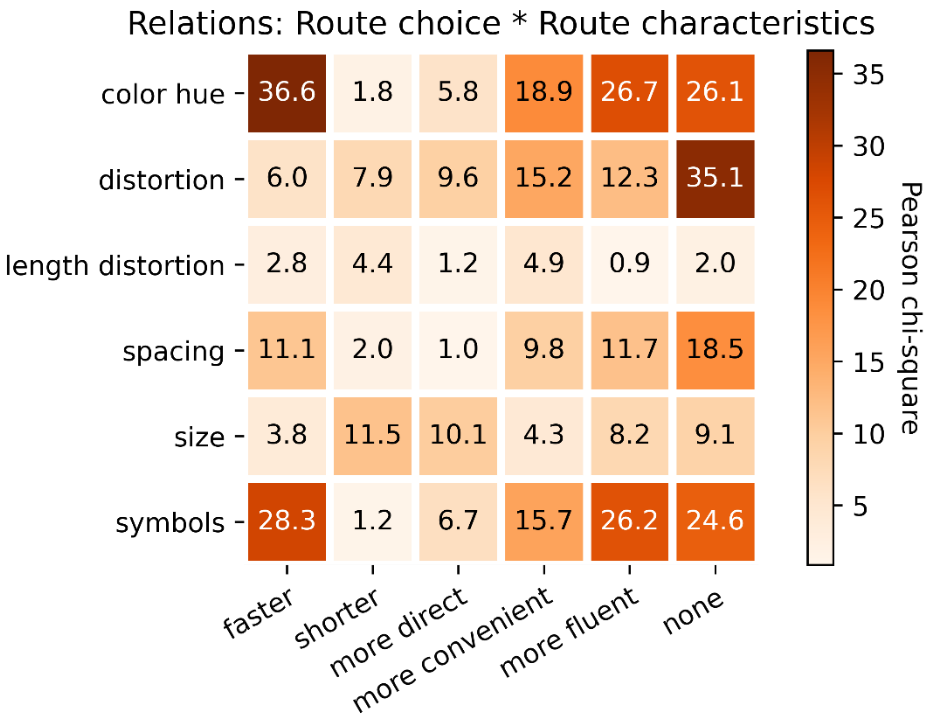


Figure 6.13: Heat map showing the relations between the route choices (design variants) and the route characteristics.

Route decisions for the design variant using *color hue* were strongly related to estimating the favorable route as *faster*, $\chi^2_{(4)} = 36.62$, $p < .001$, *more convenient*, $\chi^2_{(4)} = 18.92$, $p < .01$, $p < .001$, *more fluent*, $\chi^2_{(4)} = 26.71$, $p < .001$, and *none of this*, $\chi^2_{(4)} = 26.06$, $p < .001$.

Similarly, route decisions for the design variant using *distortion* were strongly related to estimating the favorable route as *more convenient*, $\chi^2_{(4)} = 15.18$, $p < .01$, and *none of this*, $\chi^2_{(4)} = 35.14$, $p < .001$. Further significant relations have been found with estimating the favorable route as *more direct*, $\chi^2_{(4)} = 9.63$, $p < .05$, and *more fluent*, $\chi^2_{(4)} = 12.28$, $p < .05$. Interestingly, the chi-squared test revealed that route choices for the variant using *length distortion* were not significantly related to any of the route characteristics. Route decisions for the design variant using *spacing* were related to estimating the favorable route as *more convenient*, $\chi^2_{(4)} = 9.77$, $p < .05$, *more fluent*, $\chi^2_{(4)} = 11.72$, $p < .05$, and *none of this*, $\chi^2_{(4)} = 18.53$, $p < .01$. Furthermore, there was a relation with estimating the route as *faster*, $\chi^2_{(4)} = 11.09$, $p < .05$. Route decisions for the design variant using *size* have been found related to estimating the favorable route as *more direct*, $\chi^2_{(4)} = 10.09$, $p < .05$., whereas route decisions for the design variant using *symbols* were strongly related to estimating the favorable route as *faster*, $\chi^2_{(4)} = 28.34$, $p < .001$, *more convenient*, $\chi^2_{(4)} = 15.71$, $p < .01$, *more fluent*, $\chi^2_{(4)} = 26.23$, $p < .001$, and *none of this*, $\chi^2_{(4)} = 24.56$, $p < .001$.

For design variants for which the favorable route has been chosen less often (e.g. *spacing*, *size*), it was observed that most of the characteristics have not been rated high.

6.2.8.4 Map use habits

For investigating a potential influence of map use habits on route choice behavior when using the proposed map representations, participants were asked to assess their map use habits and experiences. Using the map use habits as a between-subject variable in a repeated-measures ANOVA, there was no significant influence observable, $F_{(4, 127)} = .51$, $p > .05$. This indicates that the effects, which the different types of route visualizations seem to have on route choice behavior, do not differ significantly based on the level of experience in map reading.

6.2.9 Discussion – User study 2

The previously described survey investigated the effectiveness of different cartographic design variants of route maps for influencing route choice. In this section, the results are further discussed with a focus on the effectiveness for influencing route choice, the relation between route choice and estimated route characteristics based on the visualizations, as well as the transferability of the findings to real-world applications.

6.2.9.1 Effectiveness for influencing route choice behavior

The results of the study reveal that the six different design variants have a significantly different influence on route choice behavior, depending on the level of intensity for modification. In particular, comparing the results for the effectiveness of the different design variants, the findings show that it is possible to influence people's route choice behavior, by visually communicating temporarily favorable route options.

Some of the design variants like *length distortion* or using *symbols* seem to be generally effective for visually communicating *societally favorable* routes in the *traffic* scenario, since they influence route choice behavior at different levels of modification intensity. However, other design variants like *size* or *spacing* do not seem to have a significant impact on the participants' route decisions. This is particularly interesting since previous studies (Dong et al., 2012; Goldsberry, 2008; Lautenschütz, 2012; Kubíček et al., 2017) suggest that these representation methods could be efficient for communicating traffic-related information. However, it seems that their potential for influencing route choice behavior is limited.

Modifying route representations using *distortion* further seems to work only if the intensity of modification is applied to a stronger degree. For the design variant *length distortion*, it seems that using the *medium* intensity is already sufficient for influencing the map-reader's route choice because the difference value for *strong* intensity only slightly exceeds the value for *medium* intensity. A reason for this might be the 'obviousness' of visual recommendation, due to the favorable path being represented as geometrically shorter. Once the length ratio between the two routes exceeds a certain threshold, the (in the *modified* version) shorter route may already be perceived as favorable.

Different from the other design variants, for modifications using the visual variable *color hue*, the willingness to decide for the favorable route did not increase with the intensity of modification. In contrast, the representation with *weak* intensity seems most effective. This deviation from the trend suggests that the meaning of the used color scales may not be easy to grasp at first glance. With regard to *color hue* being generally estimated as an efficient visual variable for communicating traffic dynamics (Lautenschütz, 2012; Nelson, 2000), it is assumed that the representation using a continuous color scale (also for the road segments with low traffic density), might have confused some of the participants. That is assumed to be due to their familiarity with prevalent routing applications that show a classed visualization of road congestion, where uncongested roads are assigned only one color hue, which is typically green (Goldsberry, 2008; Lai & Yeh, 2004). Since it was not specifically controlled for color vision impairments, it might further be possible that individual differences in color vision contributed to some extent to these unusual findings.

While the 18 different routing scenarios in different cities were selected based on similar characteristics of the surrounding road network, it was unavoidable that the environments differ regarding characteristics like the density of the built environment, significant curves in the route layout, the number of crossings or the closeness to the city center. Therefore, the assumption was that the route decision is to some extent also influenced by these additional factors, and not solely based on the modifications applied for the different design variants. This may also be the reason, why for some scenarios, the route decision was for both the *non-modified* and the *modified* maps either more in favor of the favorable or the non-favorable route. However, the focus of this study was primarily to compare the *difference* values among the different conditions (the difference between route decision for *non-modified map* and *modified* map of the same routing scenario) as a measure for the willingness to decide for the favorable route, and less in the absolute results for route choice. Therefore, the analyzed data is suggested to be sufficient for measuring the influence of different cartographic design variants on route choice behavior.

6.2.9.2 The role of time during decision making

As the results indicate, for most of the routing scenarios, participants needed more time to make their route choice decision when being presented a modified map representation as compared to the non-modified representation. This result contradicts sub-hypothesis *H3*, which assumed route decisions to be made faster when viewing modified maps, due to the distinct visual highlighting of route favorability. However, the result is not surprising, since the complexity of information presented, and therefore also the expected cognitive load is higher concerning the modified maps (Bunch & Lloyd, 2006). This additional time could potentially be reduced if users would get more familiar with the different concepts for visualizing traffic density distributions. However, considering the additional information that the map-reader has to decode, the extra time needed for decision making is estimated to be small.

6.2.9.3 Relations between route choice and route characteristics

A closer look at the relations between the route choices and the estimated route characteristics provides some interesting insights. It is suggested that if a characteristic (*faster*, *shorter*, *more direct*, *more convenient* or *more fluent*) is rated high, participants who decided for the *societally favorable* route are likely to have made this choice due to the association with a route characteristic that has been evoked by the type of visualization. Particularly for design variants for which the favorable route has been chosen more frequently, high rated characteristics can provide an important hint regarding *why* the route decision has been made since these characteristics are suggested to be important criteria for route choice.

For the design variants *color hue* and *symbols*, the strongest relations have been found for the route characteristics *faster, more convenient* and *more fluent*, indicating that these characteristics might serve as important factors that have influenced route choice behavior when deciding for the favorable route. Apparently, participants who preferred the favorable route were successfully able to grasp the 'message' to be transferred by the visual metaphor.

As mentioned before, it can be assumed that (together with the estimated low suitability for visualizing favorable routes) for the design variants *size* and *spacing*, a large number of participants did not decode the applied visual metaphors correctly. In most cases, none of the options for route characteristics has been chosen. This is also reflected in the relations between route choice and characteristics. In the case of *size*, a reason for the low effect on route choice behavior could be that the used visual characteristics may have evoked ambiguous interpretations. In contrast to the associations expected for the visual metaphor (wider line = more capacity = faster / low traffic density), it could also be possible to associate the visualization with an opposite scenario (wider line = more traffic = slower / high traffic density). An evaluation of characteristics mentioned by some of the participants as *other characteristics* indicates that a similar number of participants each estimates a wider line as either efficient or inefficient**.** Therefore, a representation using a visual metaphor opposite to that (wider line = less efficient) is suggested to lead to a similar ambiguity. Due to their apparently low intuitiveness for recommending routes in terms of traffic density, the use of the visual variables *size* and *spacing* is proposed to be avoided for influencing a route decision.

Based on the preceding analysis, it becomes clear that using visual characteristics that are associated with a *faster, more convenient,* or *more fluent* travel experience have been found most important for influencing route choice. This is consistent with the literature in the field of route choice behavior, which indicates that these characteristics also serve as important route choice factors in real-world situations (Papinski et al., 2009). Therefore, it can be assumed that for example in the case of the generally influential design variant *symbols*, participants might have made a direct link to a possible real-world traffic situation - based on the visual representation. This, in turn, would have directly influenced their decision.

6.2.9.4 Transferability of the findings to real world applications

The results of this study clearly indicate that it is possible to influence the map-reader's route decision solely by using different design variants for modifying the visual map appearance. While communicating the advisability of route options, the use of different intensity levels for modification contributes to the creation of semi-realistic representations that intend to direct the viewers' attention to specific characteristics of the map and trigger a behavior change. This persuasive aspect of visual communication is observable in various types of maps (such as hazard visualizations for promoting public safety) that intend to promote a different view on things or to evoke a behavior change (Stempel & Becker, 2019; Chih & Parker, 2008; Muehlenhaus, 2012). The results of the previously described study support the assumption that this persuasive power of maps can be transferred to visually communicating routes by means of cartographic design variants (Hilton et al., 2011).

Furthermore, it needs to be considered that in a real-world setting, the motivations of a driver for choosing a route might differ from those in a laboratory setting. Also, while sitting in a car, drivers might not be able to devote their full attention to the proposed routes, since they could be distracted by additional factors that possibly influence their route choice behavior (Stutts et al., 2005).

The findings of the study suggest that particularly the visual variables that have been found influential might be suitable for implementation in a real-world routing service. With respect to safety issues caused by a potentially wrong interpretation of the information (e.g., those with geometric modifications), the modified visualizations are intended to be shown as allocentric representations in situations where a route decision has to be made; and not as egocentric visualizations during navigation. This is for example relevant in case of the *distortion* variant, since in this case a potential misinterpretation of the visualization as the actual shape of the road could lead to safety issues. Another open question is the transferability of the results to small display sizes (as commonly used for routing purposes), since here, the cognition of symbol variations could require a higher cognitive effort and thus potentially lead to longer map viewing times before making the route decision.

Although the *strong* intensity of modification has been expected to be representing the upper limit, describing up to which a visualization would be still accepted, while being useful for visually communicating favorable routes, it turned out that there is a trend that the usefulness increases with the level of intensity for modification. This raises the question, if even stronger levels of modification (resulting in more extreme use of visual variables) may result in an even higher willingness to choose the *societally favorable* route.

Based on the results of this study, further work on this topic focuses on investigating the generalizability of the proposed approach, by adapting the method to other scenarios in which a route could be recommended by traffic authorities for a particular reason (e.g. improving air quality in heavily affected areas). In this context, a possible effect of combinations of several design variants (MacEachren, 1995; Lautenschütz, 2012) on route choice behavior is investigated in user study 3.

6.2.10 Conclusion – User study 2

In this study, a set of six different design variants was compared for visually communicating *societally favorable* routes using cartographic visualization methods, with a focus on their potential for influencing route choice behavior in the context of optimizing road traffic. The findings provide evidence that it is possible to influence the map-reader's route choice towards a temporarily favorable route – using cartographic symbolization. As expected in sub-hypothesis *H1*, it has been shown that most of the applied visual modifications have a significant effect on route choice behavior (in favor of the *societally favorable* route), while the different design variants each contribute to a different extent to the map-reader's ability to assess the advisability of route options.

Figure 6.14 provides an overview of the performance of the tested design variants concerning the tested aspects *route choice* and *decision time* (separately for the three different modification intensities), as well as the estimated *route characteristics*.

Variant	Route Choice - Intensity			Decision Time - Intensity			Route char.
	Weak	*Medium*	*Strong*	*Weak*	*Medium*	*Strong*	
Color hue	↗	→	↗	↘	↘	↓	↗
Distortion	→	→	↑	↗	↗	↘	↗
Length dist.	→	↑	↑	→	↘	↓	↗
Size	↘	↘	→	→	→	↘	↓
Spacing	↘	→	→	↘	↓	↘	↘
Symbols	→	↗	↑	→	↘	↘	↗

↑	↗	→	↘	↓
Very good	Rather good	Neutral	Rather poor	Very poor

Figure 6.14: Qualitative evaluation of the performance of the tested design variants concerning different aspects, "Length dist." = Length distortion, "Route char." = Route characteristics.

While some of the design variants – like the use of *length distortion* or *symbols* for representing temporary changes in traffic density – generally seem useful for influencing the map-reader's route choice towards a *societally favorable* route, other design variants like applying variations in *size* or *spacing* only have a weak effect on the map-reader's route choices. In accordance with sub-hypothesis *H2*, for most of the proposed design variants, a significantly higher willingness to decide for the favorable route was observed, when the modifications have been visualized with a higher level of intensity. This emphasizes that map symbolization is an important factor in route choice.

The results of this study further have shown that route decisions do not depend on the time needed for decision making for most of the routing scenarios, which partly contradicted sub-hypothesis *H3*. However, different than expected, the decision time slightly increases when using a higher intensity of modification.

The willingness to choose the *societally favorable* route is strongly related to the characteristics, participants associate with a certain representation, which verified sub-hypothesis *H4*. In most cases, the favorable route has been chosen, if traveling along the route (based on the visualization) has been judged as *faster*, *more convenient*, or *more fluent*. Therefore, these characteristics are suggested to be important factors for influencing route choice behavior in the context of optimizing road traffic.

6.2.11 Modification of line objects using dynamic visual variables

The previously described user study revealed that map-readers could be influenced towards choosing a *societally favorable* route by visually modifying line objects in static route maps. Since road traffic is a dynamic phenomenon, a follow-up study has investigated, if a dynamic route map visualization using dynamic visual variables could possibly improve effectiveness for influencing route choice in the *traffic* scenario (DiBiase et. al., 1992; Köbben & Yaman, 1995).

The user study has been conducted as part of a Master's thesis research (Dare, 2021) using a similar study design, while instead of using static map visualizations, dynamic representations are used.

Each of the created design variants was prepared as a combination of one or two different static visual variables and the dynamic visual variable *duration*. Static visual variables included *spacing, color value, color hue, size, color saturation, transparency* and *distortion.* According to DiBiase and collaborators (1992) this combination can help emphasizing attributes or the relationship between attributes of cartographic features.

The dynamic component using the visual variable duration is used to control the time span of an animation. For most of the design variants, the animation goes back and forth between a visual representation for symbolizing the threshold value and a visualization that represents the original measurement value of a road segment. Hence, with a larger deviation from the threshold, the visual differences emphasized by the animation become increasingly apparent. The visual effect that is produced by the animation shows for example differences in size or color of a road segment to represent a deviation from an acceptable traffic situation.

Another type of visual effect is produced by combining the dynamic variable duration with the static variable *spacing*, which intends to give an impression of either fluency of movement or congestion along the route, depending on the speed of the animation and the size of the spacing.

The conducted user survey compared the proposed dynamic representations with a corresponding static representation and a non-modified map representation. Similar as for the previously described user study focusing on static route map visualizations, the results of this study confirmed that symbolization using dynamic variables is in general effective for influencing a traveler's route choice. However, for most of the tested design variants, effectiveness has been found to be similar for the static representations and their dynamic equivalents, indicating that dynamic visualization in route maps (as least how it has been applied in the user study) in general seems to be not more effective than static visualization. Previous studies, however, found animated maps to be more effective in terms of pattern identification and response time, when compared to static small multiple maps (Griffin et al., 2006).

In some cases, the static representation outperformed the dynamic equivalent (e.g. *duration* + *transparency*). A different observation, however, has been made regarding the variants that combine *duration* and *spacing*, since for these cases, dynamic representations have been found considerably more effective than static ones. The reason for this might be that such visualizations give an impression of a (traffic) flow or congestion by simulating an illusion of movement.

The results of this study suggest that while animated visualizations using dynamic variables that produce an illusion of movement indeed seem to increase effectiveness for influencing route choice, other variables such as color hue or transparency may perform better when being used solely as a static representation. For this reason, further usability testing as part of this thesis was focusing on static map representations.

The dynamic visualizations that have been found more effective than static representations, in this study, may directly relate to the visual metaphor of movement or (traffic) flow. Hence, it needs to be emphasized that the findings of this study and the conclusions that have been drawn might not apply to other scenarios or other potential types of dynamic visualizations. Therefore, further usability testing is required for understanding the appropriateness of dynamic visualizations for symbolizing favorability in route maps.

6.3 User study 3: Objective usability – The impact of visual communication and emotions on route choice decision making using modification of line and area objects

The previously described user study on objective usability has confirmed a general effectiveness of map symbolization for nudging a traveler's route choice towards a *societally favorable* route. However, since this study was focusing on the modification of line objects related to route visualizations in the *traffic* scenario, the results might not be applicable to other scenarios that describe areal phenomena. Therefore, a further study, which is described in this chapter, additionally considered map representations using areal modifications, as well as combinations of both types of geometry modifications. Additionally, this study compares the effectiveness of map symbols in the two different scenarios *traffic* and *air quality*. A major focus of this study is to test for a potential influence of emotional responses to map symbols, which are expected to contribute to the traveler's route choice decision. Therefore, for effectively communicating the benefit of choosing a *societally favorable* route, route maps should attempt to convey the *feeling* that the traveler might get when being exposed to societally sub-optimal traffic.

Based on the reviewed research in the fields of framing environmental communication and mapping emotions, visual variables are used to develop symbols that are proposed to be suggestive of how encountering one of two environmental phenomena along a route, *traffic* congestion or poor *air quality*, would be experienced. Since according to the concept of loss framing, communicating negative emotions is expected to be more effective for decision making than communicating positive emotions, visual modifications are primarily applied to non-favorable route alternatives (Spence & Pidgeon, 2010). In this way, the concept of framing is transferred to visual map communication (Lakoff, 2010).

The user study investigates which emotions were evoked by the map symbols and whether these emotions lead to choosing a *societally favorable* route. The same visual variables are used for representing two different environmental phenomena to test the generalizability of the visualization methods.

6.3.1 Sub-hypotheses

Before conducting the experiment, six sub-hypotheses were developed, which are derived from the key hypotheses introduced in chapter 1.2:

H1:

"A general shift towards choosing the longer, but *societally favorable* route is expected when showing the modified maps as compared to route choice for non-modified maps." (Derived from *Hypothesis 1*)

This expectation is based on previous work showing that map symbolization can be effective for influencing route choice using modifications of line features (Fuest et al., 2021).

H2:

"A higher willingness for adapting route choice behavior (showing pro-social behavior) is expected in the *traffic* condition scenario, compared to the *air quality* scenario." (Derived from *Hypothesis 2*)

This expectation is based on previous research suggesting that people feel personally unaffected by environmental impacts, and therefore also less responsible to act in a more altruistic way (Roeser, 2012).

H3:

"Line modifications are expected to be more effective for the *traffic* scenario while area modifications are expected to be more effective for the *air quality* scenario." (Derived from *Hypothesis 2*)

This expectation is based on commonly applied types of visualizations for the two different scenarios of *traffic* (Kubíček et al., 2017) and *air quality* (Lahr & Kooistra, 2010). Furthermore, a traffic jam is typically considered a linear phenomenon, whereas air quality is a continuous areal phenomenon.

H4:

"Using multiple visual variables in one map representation is expected to be more effective for influencing route choice than using a single visual variable." (Derived from *Hypothesis 1*)

This expectation is based on previous work suggesting that a conjunction of multiple visual variables can strengthen the graphic encoding of the visualised attribute (Roth, 2017).

H5:

"Routes communicated as favorable are expected to primarily evoke positive emotions, while routes communicated as non-favorable are expected to primarily evoke negative emotions." (Derived from *Hypothesis 3*)

This expectation is based on the types of emotions commonly suggested to be evoked by the symbolization as applied in the maps (Carroll et al., 2020; Kelly, 2019; Nold, 2009).

H6:

“Emotional responses to map symbols in the modified maps are expected to contribute to changing the route choice decision towards choosing the *societally favorable* route.” (Derived from *Hypothesis 3*)

Assuming correctness of *H1*, this expectation is based on previous research indicating the importance of appealing to people’s emotions related to the communicated situation for achieving route choice behavior change (Roeser, 2012).

6.3.2 Route maps

A set of 28 route maps (14 modified and 14 non-modified) was created that show parts of different real-world urban road networks. Importantly, because of the geographical distribution of the underlying data, some smaller parts of the favorable routes may contain segments that are defined as slightly non-favorable, and vice versa. Across the 14 different mapped areas, the route length ranges between 3.5 kilometers and 7.5 kilometers. This range of distances is typical of inner-city driving distances for running errands (Neumeier, 2014). The differences in path length between the different maps were not expected to have a large influence on decision making. That is, because despite the differences in length across the maps that were used in the experiment, the urban structure of the areas to be crossed is similar among the different selected areas.

Since the aim was to test realistic route choice scenarios, all route maps were created based on real environments within four different major cities in Germany, while taking care to avoid including recognizable structures in the road network to reduce the impact of participants’ familiarity with specific locations. Due to potential differences in the structural characteristics of the different real-world road networks, several potentially confounding factors were identified that should be controlled in order to minimize their likelihood of influencing route choice.

The selected route pairs 1) have the same number of turns for both route options (Venigalla et al., 2017; Parthasarathi et al., 2013); 2) use roads of similar road classes (Vreeswijk et al., 2014); 3) use the same traveling direction (Brunyé et al., 2015); 4) and have a similar road network density (Parthasarathi et al., 2013). According to Brunyé and collaborators (2010), map users tend to choose southern rather than northern routes. To ensure that all routes that were used in the experiment run from north to south, some maps have been rotated from their real-world orientation. It was initially planned to select route pairs that had the same number of left- and right-turns for each route option. However, this was difficult to achieve from a geometric point of view, so a compromise was made by having three real turns per route (not counting turn-like bends), including either two right turns and one left turn, or one right turn and two left turns. It can be noticed that the introduced route map design specifications follow a stricter pattern than those that were used for the route map design in user study 2. For example, most of the route pairs selected for user study 2 did not strictly travel from north to south. Hence, these structural differences in route map design could potentially lead to slightly different route choice results, while there are no fundamental differences to be expected.

Figure 6.15 shows the geometries of two example route pairs that fulfil these requirements. Each map was rotated (if not already in the desired orientation) so that the start and end point could be connected by an imaginary vertical line. Furthermore, for most of the route pairs, an additional version of the map was produced by rotating it 180 degrees. This was done to reduce variations in road network structures across the stimuli, while assuming participants would not identify that some images were rotated versions of other images. The road lanes selected as part of a route were adapted to the driving direction (according to right-hand driving traffic). This further reinforces the impression that all presented road networks were distinct from each other.

Figure 6.15: Two examples of route pair geometries that meet the route design requirements, each displaying one non-favorable and one favorable route. Map data from OpenStreetMap.

For defining graphical differences for constructing the modified maps, a set of observed values was used whose data source depends on the scenario and a threshold value (Fuest et al., 2023a). The observed values comprise traffic density measurements or particulate matter concentrations associated with a road segment. For both scenarios, a set of 56 observed values was used ranging between *0* and *100* (28 below and 28 above the threshold), while defining a threshold value of *50*.

Values above the threshold relate to societally non-favorable parts of the road network, while values below the threshold relate to favorable parts. The ratio of the observed value and the threshold is mapped to communicate route favorability. To make the different maps comparable, for all cases a similar distribution pattern was created – with small adjustments of the point distribution to capture the shape of the routes to achieve a more realistic distribution.

Figure 6.16 shows an example point distribution for one of the route pairs as used in the user study. The observed values were then interpolated using inverse distance weighting (IDW), before assigning the resulting raster values to the road network shapefiles. In the *traffic* scenario, although traffic congestion would normally be thought of as a linear phenomenon, the idea was to indicate congested areas where small deviations from the route to avoid congestion on a single road segment would not make the trip quicker.

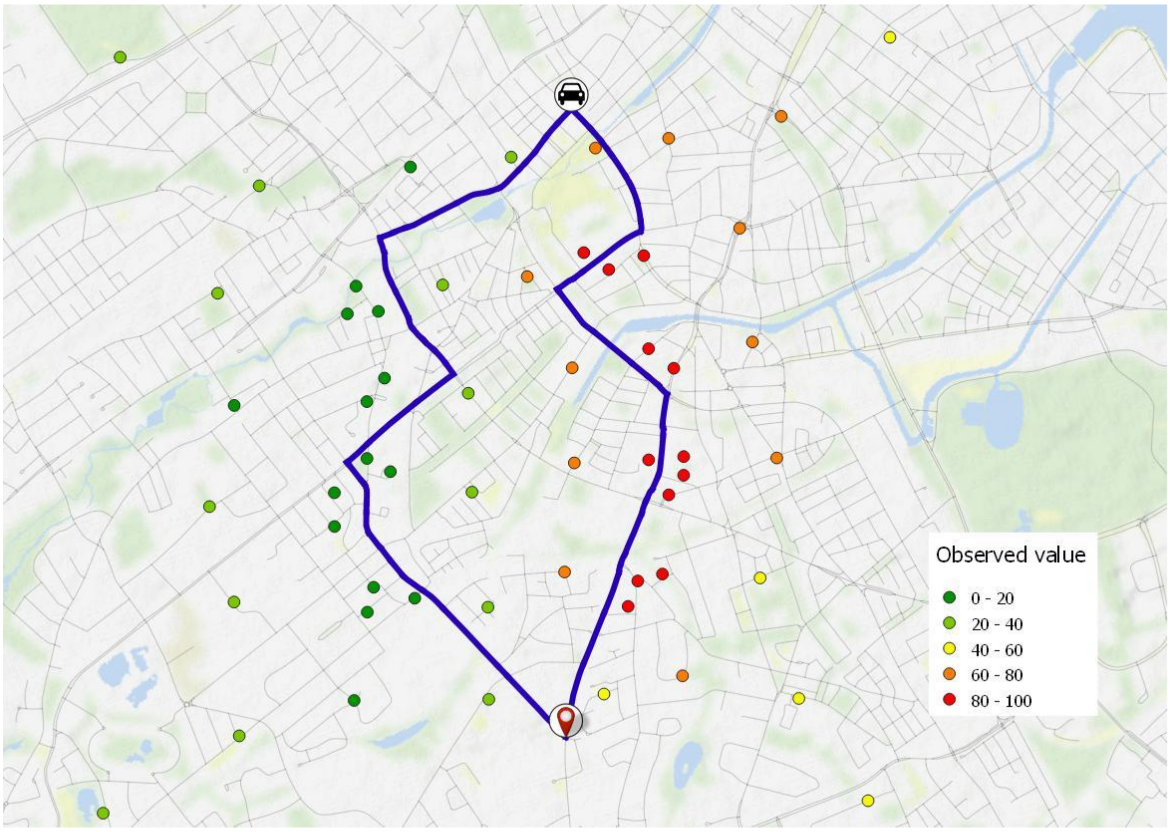


Figure 6.16: Sample route pair with point distribution of observed values. Map data from OpenStreetMap.

Figure 6.17 provides an example of a *non-modified map* where both route choices are shown with the same symbols, as compared to a corresponding *modified map* of the same area. Both map types share some common features regarding the route visualization, such as color and the icon choice. Additionally, the surrounding road network is displayed in the background using a light gray color and thinner lines. The base map shows land use categories symbolized with colors that reflect their real-world appearances (e.g., green for open space and parklands, blue for water, etc.).

In the *modified* version of the map, the shorter route is communicated as societally not favorable and the symbolization (here: line distortion and orange-brown-colored background) intends to make the route look less attractive and potentially evoke negative emotions. Therefore, the modified map tries to nudge the map-reader towards taking the longer, favorable route (here: Option B). Across the different route maps, it was varied which route option (A or B) shows the favorable route and which option shows the non-favorable route. The left-hand route is always labelled as route option A, while route option B is always shown on the right. Since the previous user study 2 has shown that map symbolization was more effective when having stronger graphical differences, for this study, it was made sure that the favorable and non-favorable route are always clearly visually distinguishable.

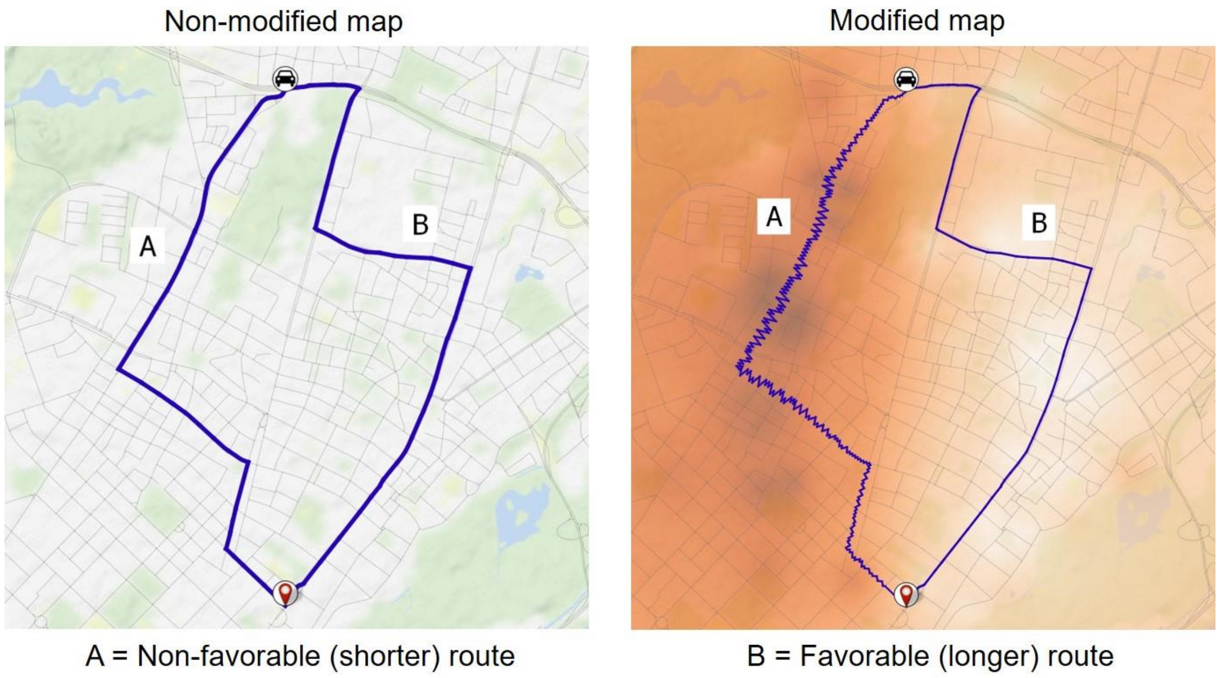


Figure 6.17: Non-modified map representation as compared to a modified map of the same route pair. Map data from OpenStreetMap.

6.3.3 Design variants

Figure 6.18 provides an overview of the 14 different design variants used in the study. For all maps, the route option that is visually communicated as favorable is marked in the figure by underlining the label *A* or *B* in red (note that in the maps as shown in the user study, this additional information was not provided). The symbol set included line, area, and line + area geometries for symbolizing temporarily favorable and non-favorable parts of the road network. The tested set of symbols included some traditional visual-variable-based approaches, such as variations in color hue, color value, size, transparency or blurring, as well as some experimental approaches for visual communication using more complex symbolization – such as line distortion, geometric deformation of areas, adding scribble to roads, or spike shapes. The corresponding non-modified maps for all 14 design variants are provided in Figure A.7 in the Appendix.

In the further course of this chapter, the following abbreviations are used, when referring to the different design variants:

Blur = *Blr*, Color Area = *CAr*, Color Distortion = *CDs*, Color Line = *CLn*, Color Spikes = *CSp*, Color Size = *CSz*, Distortion Blur = *DBl*, Deformation = *Dfr*, Distortion = *Dst*, Icons Area = *IcA*, Icons Line = *IcL*, Scribble = *Scr*, Spikes = *Spk*, Transparency = *Trp*.

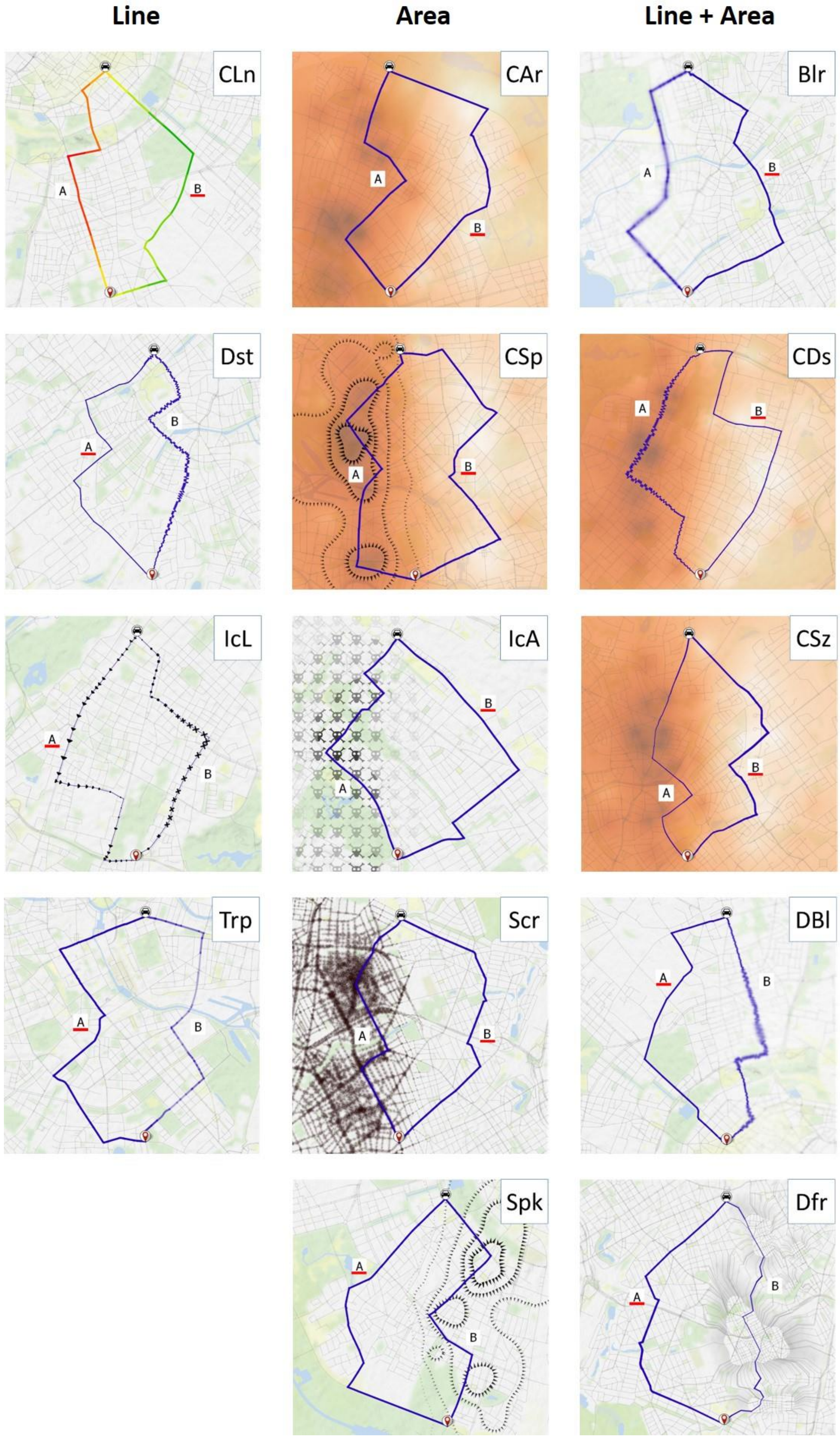


Figure 6.18: The 14 design variants as used for the user study. The route option communicated as societally favorable (A or B) is underlined in red. The visualizations modify line, area or line + area geometries. Map data from OpenStreetMap.

In general, symbols were chosen that were believed to be applicable to multiple scenarios and that therefore could potentially communicate information related to both scenarios (*traffic* and *air quality*). To ensure that participants can sufficiently see the graphical differences in the map visualizations, they saw full size images of the maps during the survey.

Two of the variants using line modifications (*CLn* and *Dst*) have been used previously in the same way in user study 2 for communicating traffic levels. Furthermore, the *IcL* variant is based on a similar concept as the previously tested variant using *symbols*, however here using more generic symbols that depend less on the communicated phenomenon, and thus are believed to be applicable to different scenarios. As a new variant, graphical variations in line transparency (*Trp*) is introduced and tested in this study.

Since the previously described user study 2 only addressed line type symbols, the variants for areal modifications are newly introduced for user study 3. However, for the combined, line + area modifications, some of the earlier introduced concepts are used again, including variations in line size and distortion, while further variants using blurring or geometric deformation, are added.

Importantly, two of the variants that have been tested in user study 2 – namely *spacing* and *length distortion* – were not used again in this study. In case of *spacing*, the choice was primarily due to its low effectiveness in the previous study. The *length distortion* variant was replaced by the *Dfr* variant in this study, which to some extent also involves a length distortion of the affected roads. This variant was suggested to better address both linear and areal scenarios than a simple line distortion. For variant *CSz*, the visual variable *size* is used, although the corresponding design variant has been found less effective in user study 2. However, in this study, it is primarily investigated, if the *size* visual variable would yield satisfactory results, when combined with a colored background area.

In the following, a detailed description of the design characteristics of the 14 different design variants for visualizing route favorability is provided.

6.3.3.1 Line modifications

Color Line (CLn)

The variant *Color Line* colors route segments based on the traffic light metaphor and equals the variant *Color hue* introduced in user study 2 (chapter 6.2.4).

Distortion (Dst)

The *Distortion* variant distorts non-favorable parts of the route and simplifies favorable parts. This variant is equal to the variant *distortion* introduced in user study 2. Because of the structure of the route segments, which already have relatively straight lines in most cases, as well as the preservation of intersections and turns, the applied line simplification is not very noticeable in the example shown in Figure 6.18. A map example with more noticeable line simplification can be found in Figure 6.5 of this thesis.

Icons Line (IcL)

The *Icons Line* variant uses different icons for representing favorable parts or non-favorable parts of the route. Favorable route segments are visualized by an arrow that points in traveling direction, non-favorable segments are represented by cross symbols that intend to prevent the traveler from driving along the corresponding route segments. Both the arrow and the cross symbols are visualized in larger size that increases with increasing difference of the observed value to the threshold. Segments with observed values that equal the threshold are visualized without adding one of the two symbol types. The concept of using a linear arrangement of symbols is applied in a similar way, but with a different symbol choice in the *symbols* variant in user study 2.

Transparency (Trp)

The *Transparency* variant uses variations in line transparency that are applied to route segments with observed values above the threshold. A higher exceedance of the threshold value is visualized by a higher transparency of the line that visualizes the segment. Route segments with observed values below the threshold are always represented as a solid line.

6.3.3.2 Area modifications

Color Area (CAr)

The *Color Area* variant adds a colored overlay on top of the existing map representation. The variations in color value derive from the observed values in the input dataset in different areas of the map. A darker color (dark orange) means a very high exceedance of the threshold value, while a light color relates to low observed values.

Color Spikes (CSp)

The *Color Spikes* variant combines the *Color Area* and *Spikes* variants (see the description below) in one map. The intent of adding the spike shapes was to intensify the visual impression that is communicated by the dark background color.

Icons Area (IcA)

The *Icons Area* variant adds a pattern composed of icons as an areal overlay. In this case, a skull icon was chosen as an icon with a negative connotation, but other alternative icons could potentially be used. While there is no icon overlay for favorable parts of the environment, areas with observed values that exceed the threshold are represented by icons with opacity that increases as the value increases.

Scribble (Scr)

The *Scribble* variant (Carroll et al., 2020) adds dark, scribbly structures on top of the road network, where the observed value for the road segment exceeds the defined threshold. The larger the exceedance of the threshold, the larger the width of the added scribble objects. Road segments with observed values below the threshold are not overlaid by scribble. This type of symbolization intends to cause visual confusion that is potentially associated with traffic disruptions or poor air quality.

Spikes (Spk)

The *Spikes* variant is based on the idea of contour lines, while the contours themselves are symbolized by a sequence of spike shapes. Contour lines are drawn depending on the level of exceedance of the threshold (for each 10 percent exceeding the threshold, a line is drawn). The more the observed values exceed the threshold, the larger the spike shapes appear. Areas with observed values below the threshold have no overlay. The sharp side of the spikes is always pointing in the direction of the traveler, when intending to enter a non-favorable area. This impression intends to prevent the traveler from traversing these areas.

6.3.3.3 Line + area modifications

Blur (Blr)

The *Blur* variant applies a blurring effect to non-favorable route segments and becomes more intense with a higher exceedance of the threshold. Favorable route segments, however, are not visually modified by this design variant. This effect is applied to both the road network and the base map.

Color Distortion (CDs)

The *Color Distortion* variant represents a combination of the *Color Area* and *Distortion* variants in one map. The distorted segments correspond directly to the coloring of the background, which intends to intensify the visual impression.

Color Size (CSz)

The *Color Size* variant extends the *Color Area* variant by adding variations in line size to the map, based on the variant *size* introduced in user study 2. This type of visualization should intensify the unattractive impression of the dark colored areas, by showing the route as a bottleneck or highly polluted area.

Distortion Blur (DBl)

The design variant *Distortion Blur* combines the *Distortion* and *Blur* variants in one map representation.

Deformation (Dfr)

The *Deformation* variant is an experimental way for visually communicating route favorability based on cartographic generalization techniques (see chapter 5.3.3). The road network that is located within non-favorable parts of the environment is deformed by applying a downscaling. The scaling factor depends on the input data, so that observed values that greatly exceed the threshold result in the road network being scaled down to a very small size. This gives an impression of a hole in the ground that the traveler may desire to avoid. While this approach distorts the original geometry, topological relations are preserved by adding *connector lines* between the scaled-down parts and the original parts of the road network. Furthermore, the scaling is also applied to the route segments (including variation in line size) that cross the scaled-down areas.

6.3.4 Study design

The study was deployed as an online survey using the German language and is based on a mixed design (see Figure 6.19). Participants were assigned randomly to one of the two scenarios: 1) *traffic*, or 2) *air quality*. Within each of these two groups, participants were asked to complete the same set of four tasks.

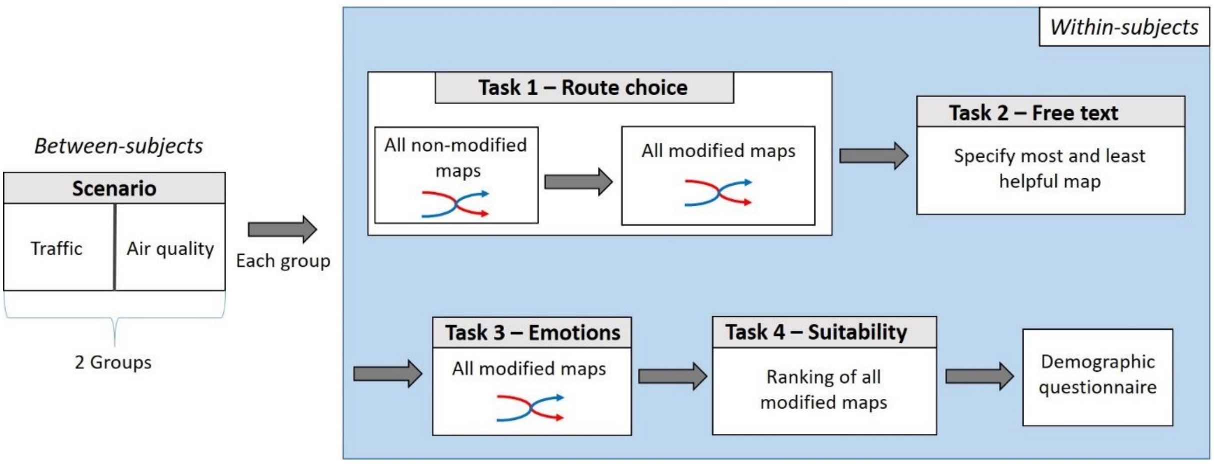


Figure 6.19: Study design of user study 3.

In the first task, participants are asked to make a route choice decision for each non-modified map, followed by each of the modified maps. For both sets of maps, the individual maps are shown in randomized order. With the used sequence, it was possible to investigate, if the difference in length between the two visualized routes has an effect on route choice (independent of knowing how the route map will look like when using symbolization). This information is used as a ground truth for comparison with the results for the modified maps to measure the effect of applying symbolization.

For the second task, participants were asked to provide free text descriptions. In the first part of the task, they were asked to describe their general strategy (or strategies) for making route choice decisions based on the non-modified and modified maps. In the second part of the task, they were required to identify which single map was most helpful and least helpful for making the route choice decision and describe the reasons for this in full sentences. For analyzing emotions, sentiment analyses using emotion lexicons (Mohammad & Turney, 2013; Hölzer et al., 1997; Vo et al., 2009) have been applied. However, as reported later, results were not sufficiently informative due to relatively short descriptions provided by most of the participants.

In the third task, participants viewed all modified maps one-by-one in randomized order, and they were asked to select the emotions they felt when viewing the *societally favorable* and *non-favorable* route in the map. To help participants describe their emotions, the German version of the Geneva Emotion Wheel was used (see chapter 2.5.2), which lists 20 emotions (ten positive and ten negative emotions), with the option to select different intensities for each emotion. Participants also have the option to choose *no* emotion or *other* emotion, in case none of the provided emotions matches their response to the map. This instrument was suitable for the purpose of this study, since it comprises most of the expected emotions related to the communicated scenarios and has been validated for German-language studies (Scherer et al., 2013). Participants were instructed to select the emotions in the corresponding intensity that best describes the feeling they have when they follow route option *A* and route option *B*. Figure 6.20 shows how this was presented in the user study, with the map on the left and the German language version of the *Geneva Emotion Wheel* on the right. The blue points indicate the positions in the wheel that one particular participant has selected. For each emotion, there are five circles that can be selected, with a larger circle that is further away from the center of the wheel representing a higher intensity of emotion. Very small circles close to the center, however, relate to a very low intensity of the selected emotion. For an illustration of the English language version of the Geneva Emotion Wheel, please refer to Figure 6.26.

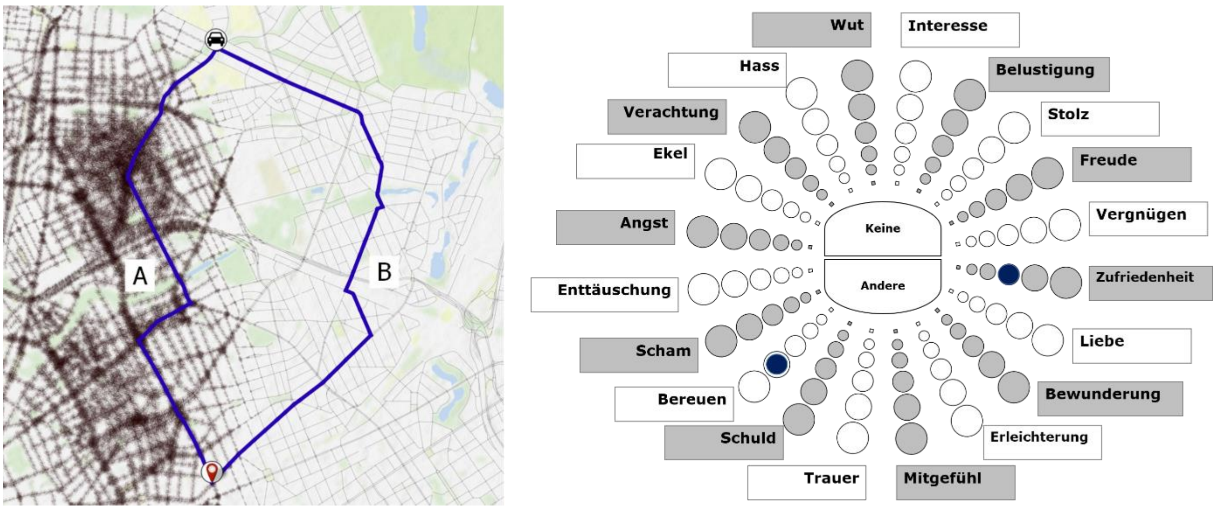


Figure 6.20: Sample visualization of task 3 as used in the user study showing the Scribble variant, with a modified map on the left and the Geneva Emotion Wheel on the right. The task looked the same for both scenarios. Clockwise translations of the emotion terms from German language: Interest, amusement, pride, joy, pleasure, contentment, love, admiration, relief, compassion, sadness, guilt, regret, shame, disappointment, fear, disgust, contempt, hate, anger. Map data from OpenStreetMap.

In the fourth task, participants were asked to rate the suitability of the visualizations. Here, participants were instructed to rate how suitable they found the maps for the presentation of the visualized information (either traffic information or air quality information) by ranking them from most to least suitable. The experiment concluded with a demographic questionnaire focusing on travel behavior and map usage.

In addition to providing information on gender and age, participants were asked questions about their use of navigation systems while driving, experience with maps, and familiarity with map visualizations. To control for a possible impact of visual impairments, participants were also asked to indicate if they have corrected vision and if they have a red-green visual impairment. Lastly, to control for any bias related to preferences for the left- or right-hand side of a visual representation, participants were also asked about their handedness.

The study was developed using the *Lime Survey* platform and was made accessible to potential participants by distributing the access link. All participants were informed about the aim of the study and the study procedures and agreed to specifications regarding data anonymization and data analysis. In particular, the collected data does not include information that reveals a person's identity.

6.3.5 Participants

Most of the participants were either students or staff members at the authors' university or German-speaking participants from other universities or research institutes in Germany, Austria, and Switzerland.

A dataset consisting of 126 complete responses (*traffic* scenario: $n = 73$, *air quality* scenario: $n = 53$) has been used for analysis. The noticeable difference in sample size for the two different scenarios is due to the fact that participants in the *air quality* scenario dropped out of the survey more frequently than did participants in the *traffic* scenario. The reason for participants dropping out more frequently in the *air quality* scenario is likely that some people thought the topic is not relevant to them, or due to difficulties with expressing emotions related to air pollution. An evaluation of the point in time when participants frequently dropped out of the survey revealed that the majority of participants cancelled their participation at a relatively early stage, during the route choice task. This observation is similar for both the *traffic* and *air quality* scenario groups, however, in the *air quality* scenario, comparatively more participants dropped out when the modified maps (and along with that the air quality topic) have been introduced. A second, less distinct peak is observable when introducing the emotion-related task. Participants in the *traffic* scenario (34 female, 38 male, 1 not specified) ranged in age from 19 to 67 years ($M = 28.85$, $SD = 11.42$), while participants in the *air quality* scenario (27 female, 22 male, 2 diverse, 2 not specified) ranged in age from 18 to 64 years ($M = 30.49$, $SD = 13.25$). Two participants indicated they had a red-green visual impairment. Therefore, these responses have been removed from the analysis.

The majority of participants (91.3 %) indicated having driving experience, while the remaining participants (8.7 %) never drove a car.

Since many of the participants have a cartography-related background, experience in map usage is relatively high: 25.4 % experts, 49.2 % frequent users, 21.4 % occasional users, while only 4 % reported they had no experience in map usage. Similarly, most participants are familiar with common map visualizations: 10.3 % estimate themselves as experts, 46.8 % reported they had a good overview, 37.3 % have a general overview, while 2.4 % report having no overview of map visualizations. 3.2 % reported that they were not sure how to answer this question.

6.3.6 Results – User study 3

The results of the study were analyzed with a focus on testing the sub-hypotheses, including the influence of the design variants on route choice and the role emotions play when making a route choice decision.

6.3.6.1 H1: Shift towards choosing the societally favorable route

Results regarding route choice preferences for the non-modified maps support the sub-hypothesis that most would choose the shorter route option – the route which is communicated as non-favorable in the modified maps: 70.7 % of all responses for the non-modified maps indicated the participant would *rather* or *definitely* prefer the shorter route option.

Figure 6.21 provides a first impression regarding the users' route choice preferences for the modified maps. For each design variant, the figure shows the percentage of route choice preferences based on the 5-point Likert scale as used in the survey for the two different scenarios, *traffic* and *air quality*. In both scenarios, users tended to choose the route that was communicated as favorable. However, there are distinct differences observable between the scenarios, as well as among the different design variants.

In the *traffic* scenario, people are more likely to *definitely* choose the *societally favorable* route. In the *air quality* scenario, however, users predominantly selected they would *rather* choose the favorable route. This suggests that the visual communication may have been less effective for the *air quality* scenario.

When comparing route choice preferences for the different design variants, it can be observed that for most of the variants such as *Color Line* (*CLn*), *Color Distortion* (*CDs*), or *Icons Line* (*IcL*), most participants chose *rather* or *definitely* the favorable route.

In case of the *Transparency* (*Trp*, both scenarios) and *Color Area* (*CAr*, *traffic* scenario) variants, however, a relatively large percentage of participants chose *rather* the non-favorable route, indicating that for these variants, visual communication did not have the desired effect.

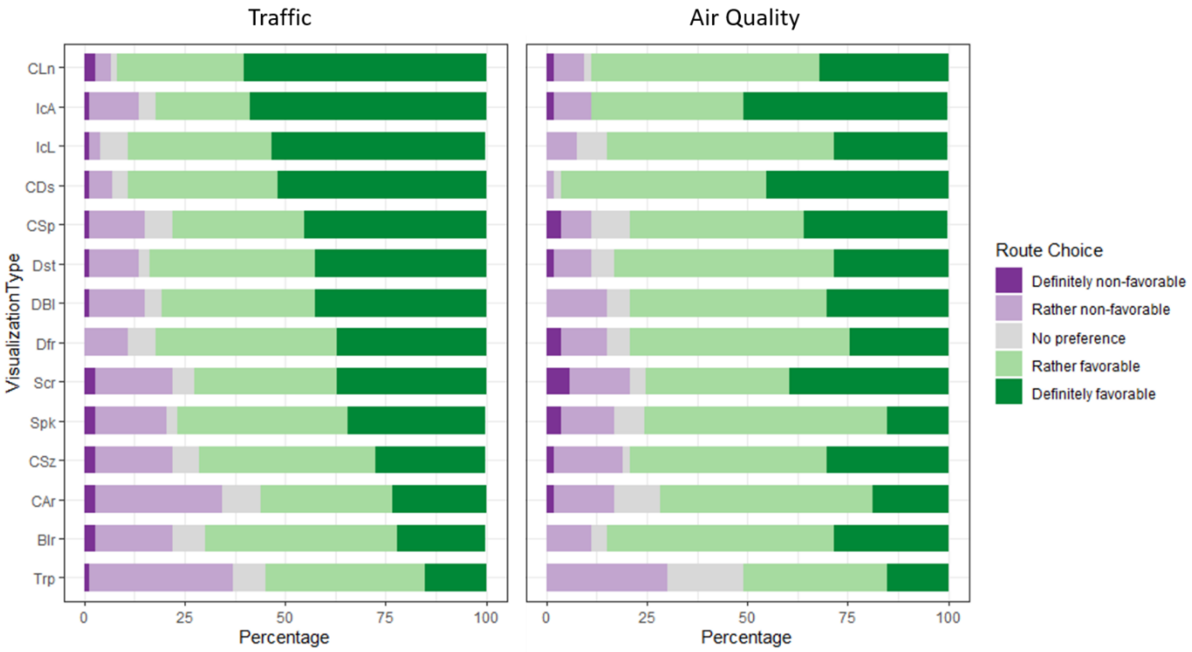


Figure 6.21: Route choice preference percentages for the modified maps, based on the 5-point Likert scale.

To test whether participants' responses were affected by the map modifications, it was examined whether there was a shift to choosing the *societally favorable* route in the modified maps as compared to the non-modified maps. Figure 6.22 illustrates the route choice results for the modified maps and the corresponding non-modified maps for the 14 different design variants, considering the two scenarios separately. The 5-point scale data were recoded such that a higher value indicated a greater preference for the favorable route: 1 = Definitely non-favorable, 2 = Rather non-favorable, 3 = No preference, 4 = Rather favorable, 5 = Definitely favorable. The route choice results for the different design variants are shown in descending order based on the results for the *traffic* scenario. The vertical line depicting the option *no preference* (value 3 at the x-axis) as a threshold between favored and non-favored maps has been visually highlighted to facilitate estimating trends in the data.

As shown by the mean values being less than three, unsurprisingly, in most cases participants chose the shorter route option (i.e., the unfavorable route) when viewing the non-modified maps. In the modified maps, it can be observed a clear shift towards choosing the longer, favorable route for all design variants in both scenarios.

In other words, visual communication for influencing route choice generally seems to have worked as predicted in sub-hypothesis *H1*. However, there are some interesting differences between the variants. Unsurprisingly, the widely used and generally well-known *Color Line* (*CLn*) variant was effective, but participants' preference for the *societally favorable* route was higher for the *traffic* scenario than the *air quality* scenario. Other variants such as *Transparency* (*Trp*) or *Color Area* (*CAr*) seem to be less effective. The efficacy also seems to increase when combining the *CAr* variant with other visual variables – for example for the variants *CDs*, *CSz*, and *CSp*. In general, it can also be observed that visualizations that only modify lines were more effective in the *traffic* scenario, while areal modifications were more effective for the *air quality* scenario, as predicted in sub-hypothesis *H3*.

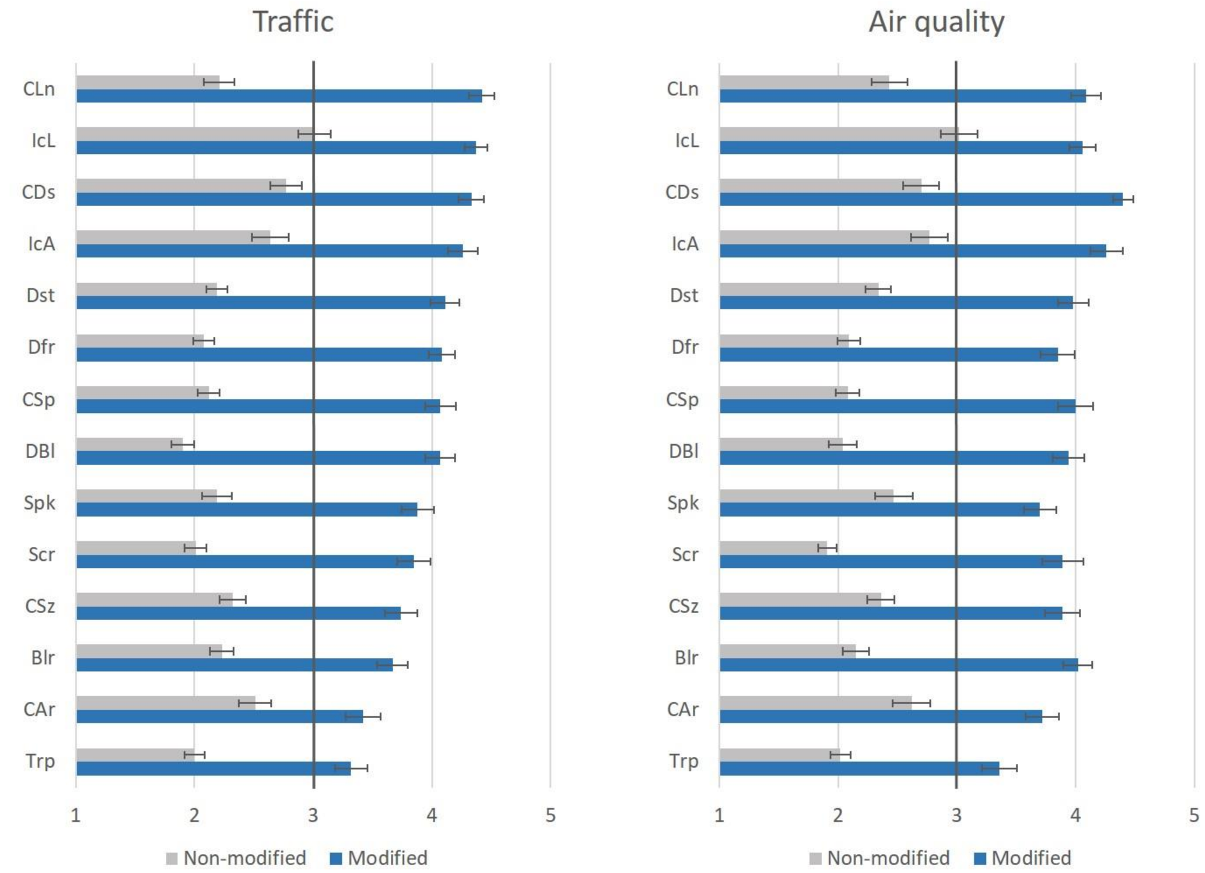


Figure 6.22: Mean route choice results for the non-modified and modified maps based on the 5-point Likert scale (1 = definitely non-favorable, 2 = rather non-favorable, 3 = no preference, 4 = rather favorable, 5 = definitely favorable). The error bars indicate the standard error.

To assess whether the variables *modification*, *design variant* and *scenario* have an influence on participants' route choice, ordinal regression was performed by defining a *Cumulative Link Mixed Model (CLMM)*, using the *ordinal* and *emmeans* packages in *R*.

To verify that the sample size was appropriate for performing ordinal regression, a post-hoc power analysis was performed using the R package "popower" (Whitehead, 1993). Since the primary aim in this study was to compare modified vs. non-modified maps, the power analysis was done based on the factor *modification*. Because the analysis has been done as a post-hoc power analysis, the actual proportions were used to calculate the odds ratio rather than the expected proportions. Since the proportions of choosing the favorable route differ considerably between modified and non-modified maps, a very high odds ratio (OR) of 17.31 could be obtained. Consequently, considering the sample sizes for both scenarios, a power of one was achieved in both cases. Hence, it can be concluded that the sample data was appropriate for performing the regression analysis.

The first ordinal regression model tested the influence of map *modification* (*modified* or *non-modified*) and *design variant* on route choice, while considering the data from the two scenarios in separate analyzes (*traffic* scenario: $R^2_{Nagelkerke} = .48$; *air quality* scenario: $R^2_{Nagelkerke} = .51$). For both scenarios, ANOVA results reveal a significant main effect of *modification* (*traffic* scenario: X^2 (1, N = 73) = 1016.14, p < 2.2e-16; *air quality* scenario: X^2 (1, N = 53) = 807.01, p < 2.2e-16), and *design variant* (*traffic* scenario: X^2 (13, N = 73) = 138.43, p < 2.2e-16; *air quality* scenario: X^2 (13, N = 53) = 107.05, p < 2.2e-16). Furthermore, a significant interaction effect was found for *modification* and *design variant* (*traffic* scenario: X^2 (13, N = 73) = 68.56, p = 1.476e-09; *air quality* scenario: X^2 (13, N = 53) = 35.78, p < .001), indicating that for different design variants, route choice behavior differs depending on the modification type.

Pairwise comparisons among estimated marginal means (EMMs) further confirm a significant difference of route choice between *non-modified* and *modified* maps for all design variants. Table 6.8 summarizes the mean route choice values (for *non-modified* and *modified*), the difference between the non-modified and modified preferences (*shift*) and test statistics (*estimate*, *z*-score and *p*-value), as well as the effect size (Cohen's *d*) for the *traffic* and *air quality* scenarios. Except for the variant *CAr* (*medium effect* for both scenarios), a *large effect* was found for all design variants in both scenarios regarding the difference between route choice for the non-modified and corresponding modified map. Taking the design variant *Distortion Blur (DBl)* in the *traffic* scenario as an example, the following conclusions can be drawn from the table: While users on average chose rather the shorter, non-favorable route in the non-modified maps (value for *n.-mod* close to 2), route choice has been influenced considerably when showing the modified map, towards on average choosing rather the longer, but *societally favorable* route (value for *mod.* that was close to 4).

*Table 6.8: Mean route choice values (non-modified (n.-mod.), modified (mod.)), shift variable and statistics for EMM pairwise comparisons (estimate (est.), z-score and p-value), n = 73 (traffic), n = 53 (air quality), *** p <.001. P-value adjustment using the Tukey method. Effect size (Cohen's d): small effect: 0.2 ≤ d < 0.5; medium effect: 0.5 ≤ d < 0.8; large effect: d ≥ 0.8 (Cohen, 1988).*

Variant	Traffic							Air quality						
	n.-mod.	*mod.*	*shift*	*est.*	*z*	*p*	*d*	*n.-mod.*	*mod.*	*shift*	*est.*	*z*	*p*	*d*
Blr	2.23	3.67	1.44	-2.41	-7.79	**<.001*****	1.11	2.15	4.02	1.87	-3.85	-9.78	**<.001*****	1.47
CAr	2.51	3.42	.91	-1.69	-5.34	**<.001*****	.59	2.62	3.72	1.1	-2.24	-5.79	**<.001*****	.75
CDs	2.77	4.33	1.56	-2.87	-8.79	**<.001*****	1.01	2.7	4.4	1.7	-3.66	-9.25	**<.001*****	1.41
CLn	2.21	4.42	2.21	-4.41	-12.59	**<.001*****	1.57	2.43	4.09	1.66	-3.5	-8.78	**<.001*****	1.26
CSp	2.12	4.07	1.95	-3.54	-10.85	**<.001*****	1.5	2.08	4	1.92	-4.01	-10.2	**<.001*****	1.66
CSz	2.32	3.74	1.42	-2.52	-8.06	**<.001*****	1.01	2.36	3.89	1.53	-3.15	-8.18	**<.001*****	1.09
DBl	1.9	4.07	2.17	-4.12	-12.43	**<.001*****	1.62	2.04	3.94	1.9	-4.11	-10.3	**<.001*****	1.77
Dfr	2.08	4.08	2	-3.54	-11.05	**<.001*****	1.7	2.09	3.85	1.76	-3.61	-9.34	**<.001*****	1.51
Dst	2.19	4.11	1.92	-3.37	-10.47	**<.001*****	1.5	2.34	3.98	1.64	-3.27	-8.51	**<.001*****	1.22
IcA	2.64	4.26	1.62	-3.26	-9.41	**<.001*****	.98	2.77	4.26	1.49	-3.42	-8.44	**<.001*****	.98
IcL	3.01	4.37	1.36	-2.53	-7.8	**<.001*****	.93	3.02	4.06	1.04	-2.15	-5.66	**<.001*****	.84
Scr	2.01	3.85	1.84	-3.36	-10.35	**<.001*****	1.35	1.91	3.89	1.98	-4.4	-10.84	**<.001*****	1.59
Spk	2.19	3.88	1.69	-3.18	-9.64	**<.001*****	1.09	2.47	3.7	1.23	-2.54	-6.63	**<.001*****	.98
Trp	2	3.32	1.32	-2.36	-7.45	**<.001*****	.92	2.02	3.36	1.34	-2.67	-6.94	**<.001*****	1.04

Similar as done for user study 2, for further analysis, the difference between the mean route choice values has been calculated for the modified maps and those for the non-modified maps as a new variable. For this, the values for the non-modified maps have been subtracted from the values for the modified maps. The resulting values provide information regarding the magnitude of the *shift* towards choosing the favorable route or the non-favorable route (see respective columns in Table 6.8). A positive value indicates a shift towards choosing the favorable route in the modified map, as compared to the route preference for the corresponding non-modified map, while a negative value (not observed here) would represent a shift towards choosing the non-favorable route in the modified maps. Figure 6.23 visualizes the results for this *shift*.

Ordinal regression has been applied to test whether there is a difference regarding the scenario and the visualization type. The dependent variable was the *shift*, the independent variables were *scenario* and *visualization type*. The regression model provided results that are very similar to those for route choice for the modified maps ($R^2_{Nagelkerke} = .24$). Again, a significant main effect is observed for the *visualization type* (X^2 (13, N = 126) = 115.28, p = < 2e-16), but not for *scenario* (X^2 (1, N = 126) = .66, p = .42). An interaction effect for scenario and visualization type (X^2 (13, N = 126) = 23.85, p = .03) has also been found significant for the *shift*. The similarity of results for *route choice* and *shift* confirms the adequateness of route pair selection. Hence, for further analysis, the focus was on the *route choice* data, instead of using the *shift* data.

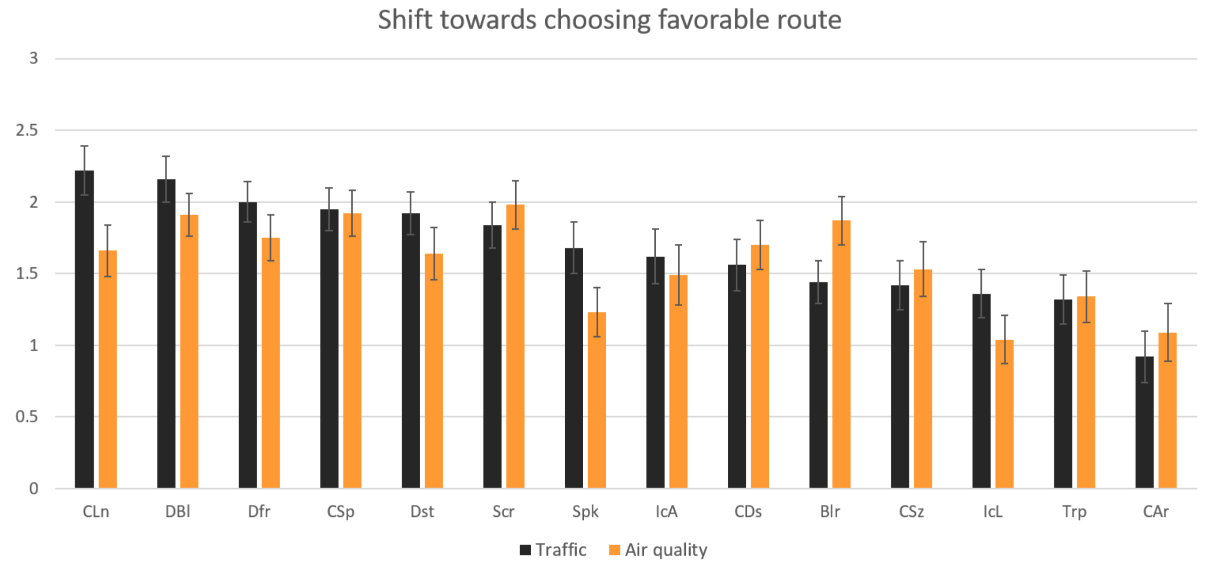


Figure 6.23: Shift in route choice between non-modified and corresponding modified maps. The error bars indicate the standard error.

6.3.6.2 H2: Scenario-dependent willingness to adapt route choice behavior

In a next step, the influence of the scenario (*traffic* or *air quality*) and design variant (14 design variants of route maps) on route choice for the modified maps, was tested. For that, two-way repeated-measures ordinal regression was applied with *CLMM*. The regression model was defined by using *route choice* as the dependent variable, and *scenario* and *design variant* as independent variables (fixed effects), and *participant* as a random effect.

The results for the regression model ($R^2_{Nagelkerke} = .41$) showed a significant main effect for the *design variant* (X^2 (13, N = 126) = 201.59, p < 2e-16), but not for *scenario* (X^2 (1, N = 126) = .73, p = .39). This indicates that the type of visualization used in the modified maps has a significant influence on route choice. Different than predicted in sub-hypothesis *H2*, the main effect for *scenario* was not significant. However, a significant interaction effect was found for *scenario* and *design variant* (X^2 (13, N = 126) = 32.04, p = .002), indicating that for different design variants, route choice behavior differs depending on the scenario.

Post-hoc comparisons comparing different design variants revealed that route choice behavior differs significantly between many visualization pairs. In particular, *Transparency (Trp)* differs from most of the other design variants in terms of its effectiveness. Participants were significantly less likely to choose the *societally favorable* route when viewing the *Trp* variant as compared to other design variants; ten visualization pairs were significantly different in the *traffic* scenario, six pairs in the *air quality* scenario. For the *traffic* scenario, the smallest significant difference was for the pair *Trp, Scr* (*estimate* = -1.3), while the largest difference is reached by the pair *Trp, CLn* (*estimate* = -2.97). Similarly, for the *air quality* scenario, the smallest significant difference is observed for the pair *Trp, Blr* (*estimate* = -1.52), while the largest difference is reached by the pair *Trp, CDs* (*estimate* = -2.62).

6.3.6.3 *H3: Scenario-dependent effectiveness of symbolization dimensions*

To examine whether the effectiveness of different symbolization dimensions (line, area, line + area) depends on the scenario (*H3*), an ordinal regression model was constructed with *scenario* and *symbolization dimension* as independent variables, *route choice* as the dependent variable and *participant* as a random effect. Results for the regression model ($R^2_{Nagelkerke} = .31$) reveal that the *symbolization dimension* did not have an effect on route choice (X^2 (2, N = 126) = 1.4, p = .5), but the interaction between *scenario* and *symbolization dimension* was significant (X^2 (2, N = 126) = 7.67, p = .02). This indicates that for the different symbolization dimensions, route choice behavior differs depending on the scenario – supporting the assumption of line type modifications would be more effective for the *traffic* scenario and area type modifications would be more effective for the *air quality* scenario.

However, pairwise comparisons did not show any significant relationships between scenarios and dimensions. This can be explained by the relationship between the ANOVA and the (Tukey) post-hoc test not being one-to-one. Thus, non-significant post-hoc results might be due to pairwise comparisons not considering the distribution of all tested group means as a whole. Hence, the distribution of means (clustered or even) could lead to different results for the ANOVA. In summary, it seems that sub-hypothesis *H3* is to some extent supported, but as post-hoc results have shown, a scenario-dependent difference in effectiveness of symbolization dimensions could not be statistically verified.

6.3.6.4 H4: Influence of combining multiple visual variables in one representation

To test the sub-hypothesis (*H4*) that combined design variants were more likely to influence participants to choose the favorable route than visualizations that only modified either linear or areal features, it was examined whether there is a difference in route choice between single-feature modifications and combined modifications that include an additional visual variable for communicating the information.

Figure 6.24 visualizes the mean values for route choice between *single* (one visual variable used) and the corresponding *combined* (more than one visual variable used) visualizations. Single feature modifications are shown at the far left of each graph.

While being less effective on its own, the *Color Area* (*CAr*) variant, when combined with additional visual variables, increases participants preferences for the favorable route, with the strongest preferences expressed for the *Color Distortion* (*CDs*) variant. Moreover, this pattern is consistent in both scenarios. For the *Blur* (*Blr*), *Distortion* (*Dst*), and *Spikes* (*Spk*) variants, however, a combination with additional visual variables did not significantly improve effectiveness for influencing route choice. While adding visual variables such as spikes or distortion to the color-based *CAr* variant was useful for improving effectiveness, adding color or blurring as an additional visual variable was less effective. In other words, combinations of several visual variables might be beneficial for some design variants such as those involving colors, while for other variants, combinations are less useful. In contrast to the other tested single feature modifications, it seems that in case of the *CAr* variant, adding other (mainly line type) visual variables successfully intensifies the visual communication of favorable and non-favorable routes.

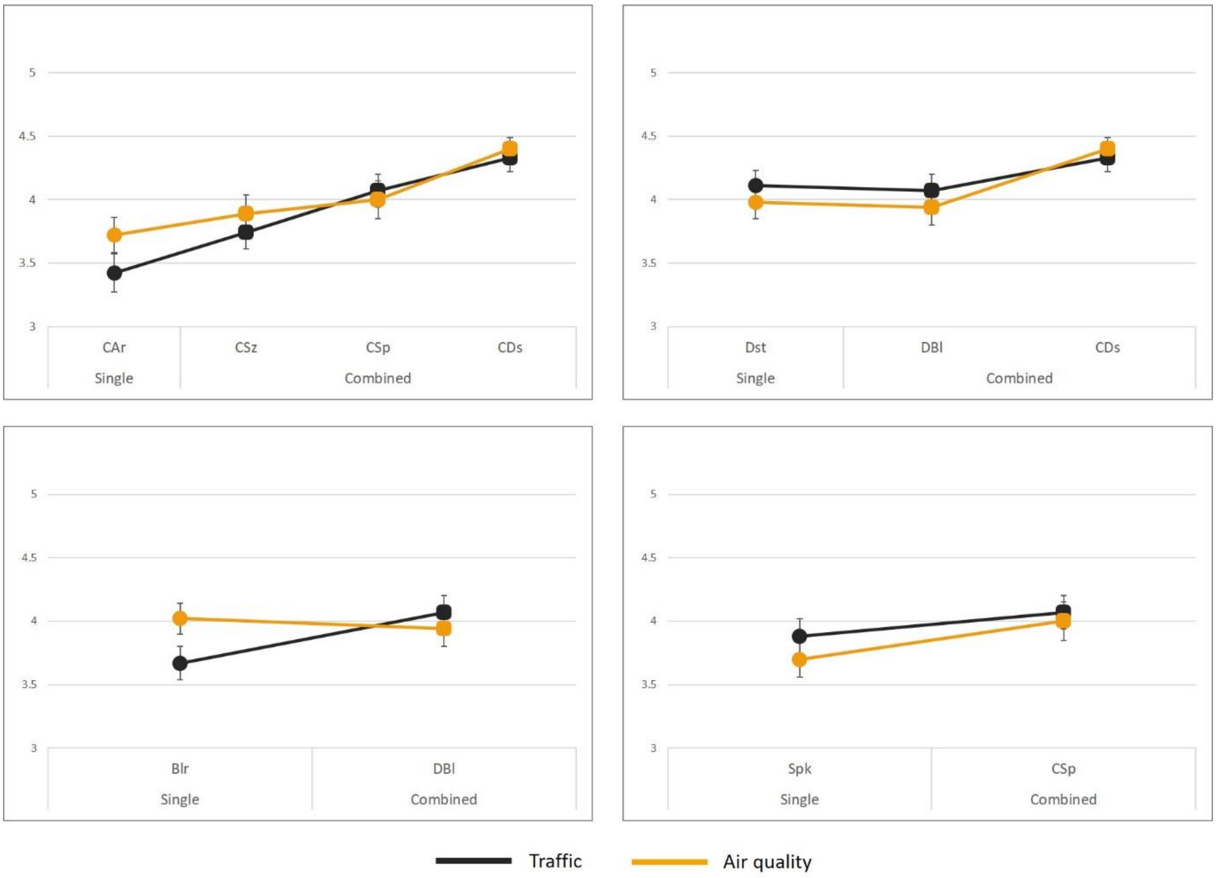


Figure 6.24: Comparison of mean route choice values between single and corresponding visualizations combining several visual variables. Error bars depict standard errors.

Post-hoc comparisons of the CLMM for the *route choice* data (see Table 6.9) reveal a statistically significant difference between the variants *Color Area (CAr)* and *Color Distortion (CDs)* for both scenarios. In addition, the difference in route choice between the variants *Color Area (CAr)* and *Color Spikes (CSp)* was significant for the *traffic* scenario. All three combinations had a medium effect size.

*Table 6.9: Test statistics (estimate (est.), z-score and p-value) for the difference in route choice (for modified maps) between single and combined design variants, n = 73 (traffic), n = 53 (air quality), * p <.05, ** p < .01, *** p < .001. Effect size (Cohen's d): small effect: 0.2 ≤ d < 0.5; medium effect: 0.5 ≤ d < 0.8; large effect: d ≥ 0.8 (Cohen, 1988).*

Variants	Traffic				Air quality			
	est.	*z*	*p*	*d*	*est.*	*z*	*p*	*d*
CAr → CSz	-.66	-1.96	.978		-.52	-1.36	1	
CAr → CSp	-1.54	-4.42	**.003****	.54	-.82	-2.18	.925	
CAr → CDs	-2.18	-6.13	**<.001*****	.72	-1.86	-4.69	**<.001*****	.78
Dst → DBl	-.04	-.12	1		0	0	1	
Dst → CDs	-.72	-2.02	.968		-1.24	-3.1	.287	
Blr → DBl	-1.21	-3.57	.081		.14	.36	1	
Spk → CSp	-.58	-1.67	.998		-.91	-2.38	.828	

6.3.6.5 H5: Emotional responses to map symbols

In the following section, the results related to the participants' felt emotions are described, which are based on the data collected using the *Geneva Emotion Wheel*.

Following the common categorization of emotions into positive and negative valence as proposed in the circumplex model of emotions (Russell, 1980), emotion terms were categorized into negative and positive emotions. Figure 6.25 provides an overview of the percentages of participants who felt *positive, negative, no* emotion, or *other* emotions related to the *societally favorable* and the *non-favorable* route for the 14 different design variants, separately for the *traffic* and *air quality* scenarios. As hypothesized in *H5*, favorable routes have been mainly associated with positive or no emotions, while non-favorable routes have been mainly associated with negative emotions. However, there are some interesting differences between the design variants, as well as between the scenarios. For example, it can be observed that for most of the variants the non-favorable route has evoked negative emotions among a higher percentage of participants in the *air quality* scenario – particularly for those design variants that visualize areal features. This might be related to negative emotions associated with air pollution (Böhm & Pfister, 2008). For positive emotions, the differences between the scenarios were smaller. However, design variants involving a color area background (*Color Area* (*CAr*), *Color Size* (*CSz*), *Color Spikes* (*CSp*), *Color Distortion* (*CDs*)) generally evoked a higher proportion of negative emotions even among the favorable routes. This, again, is particularly observable for the *air quality* scenario.

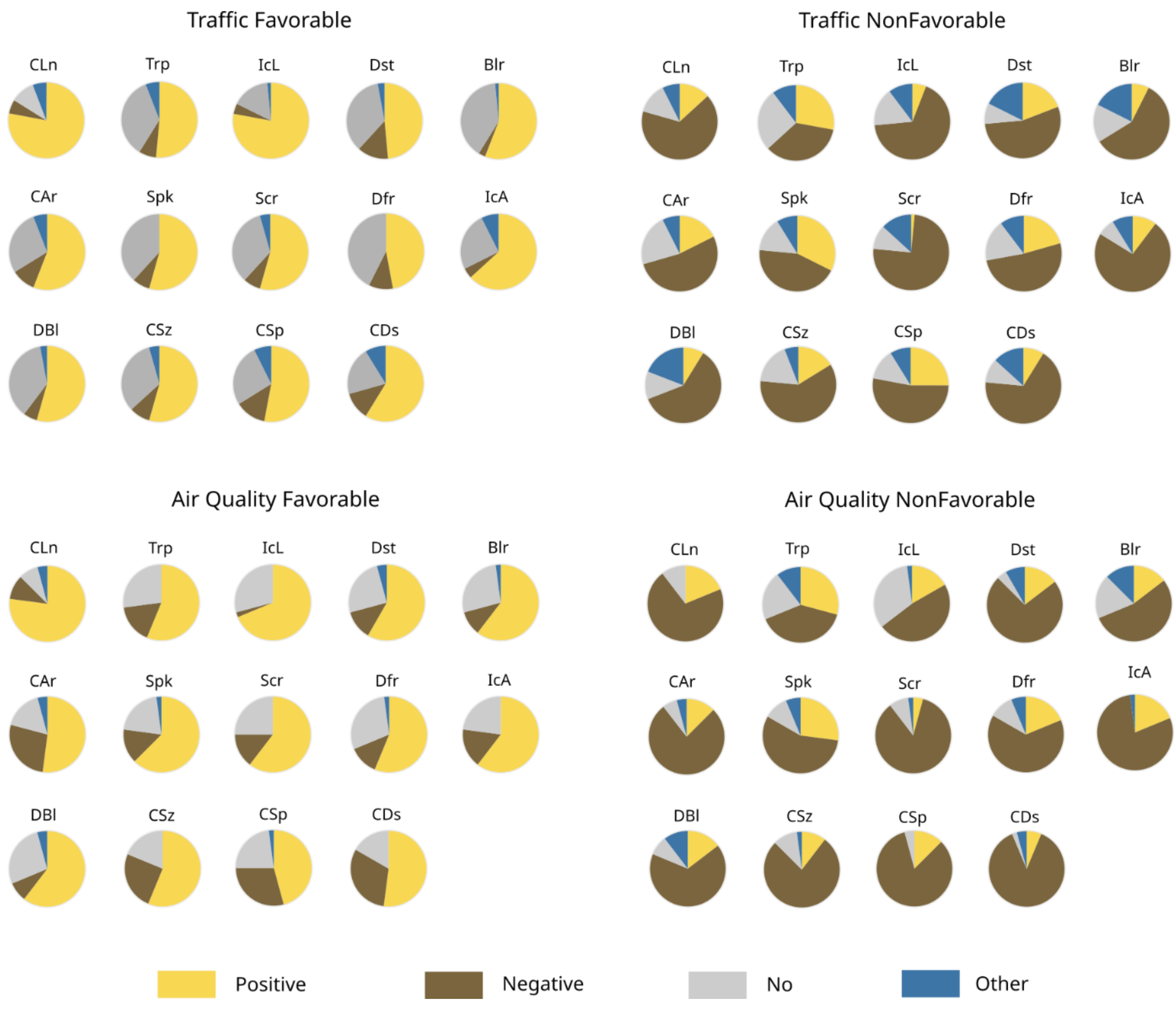


Figure 6.25: Percentages of emotions felt related to the different design variants for the societally favorable and non-favorable route in the two different scenarios traffic and air quality. Emotions have been classified into positive, negative, no (emotion), and other (emotion).

In Figure 6.26, the variety of emotions is shown that have been felt for the design variant *Scribble (Scr)* in the *traffic* scenario as an example. It is clear that participants felt mostly positive emotions (or no emotions) about the *societally favorable* route, while they felt mostly negative emotions for the non-favorable route.

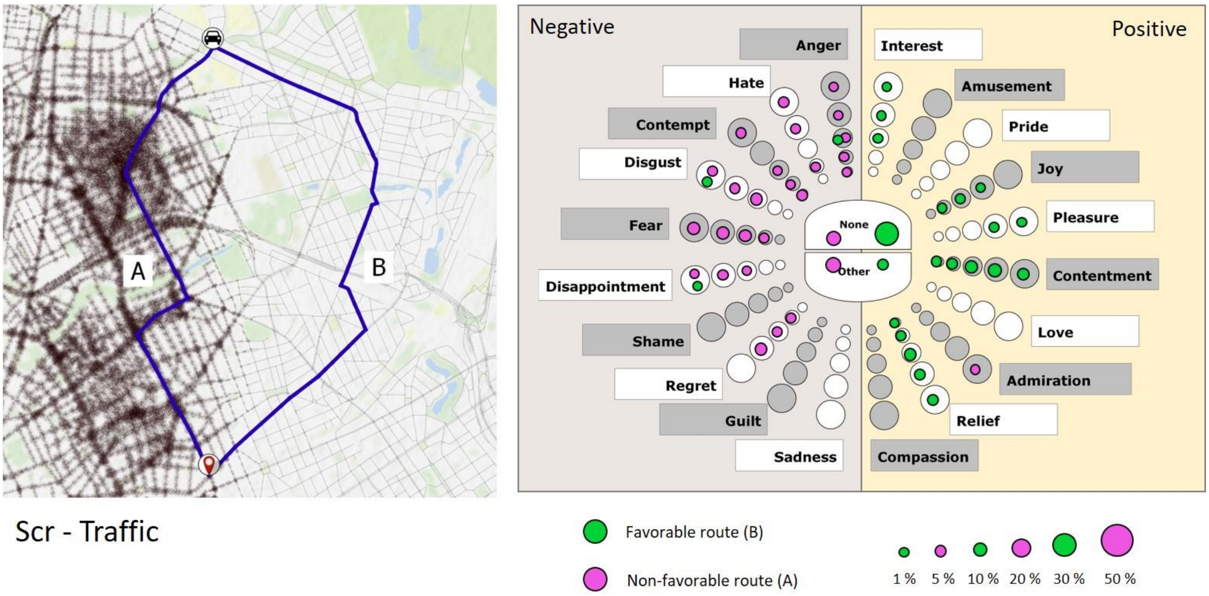


Figure 6.26: Percentages of felt emotions, visualized on top of the Geneva Emotion Wheel for the Scribble (Scr) variant in the traffic scenario. Map data from OpenStreetMap.

Figures 6.27-29 show the percentages of felt emotions for the two different scenarios, as well as for the favorable and non-favorable route in the form of spider charts. The outer circle of each chart represents a value of 60 % of all felt emotions as a reference, which relates to the maximum value observed in the data for a single emotion. The results reveal some interesting patterns. While *societally favorable* routes mainly evoke either no emotions or positive emotions such as *contentment* or *relief*, the emotions felt for non-favorable routes are more diverse. For many of the design variants, the non-favorable route seems to have evoked the emotion *fear*. This is particularly the case for the variants *Scr*, *IcA*, *Dfr*, and the color-based variants *CAr*, *CSz*, *CSp* and *CDs*. But other negative emotions such as *anger*, *disappointment*, *regret*, or *disgust* have also been felt relatively often. While the emotion *anger* has been felt by a particularly high percentage of participants for the *Color Line* (*CLn*) variant in the *traffic* scenario, the emotion *disgust* has mostly been felt when looking at the color-based variants in the *air quality* scenario and the *Scribble* (*Scr*) variant. In several cases, the positive emotion *interest* has been selected for the non-favorable route. This might be due to interest in what the visualization intends to communicate, and therefore could be a potential sign of ambiguity of the symbolization.

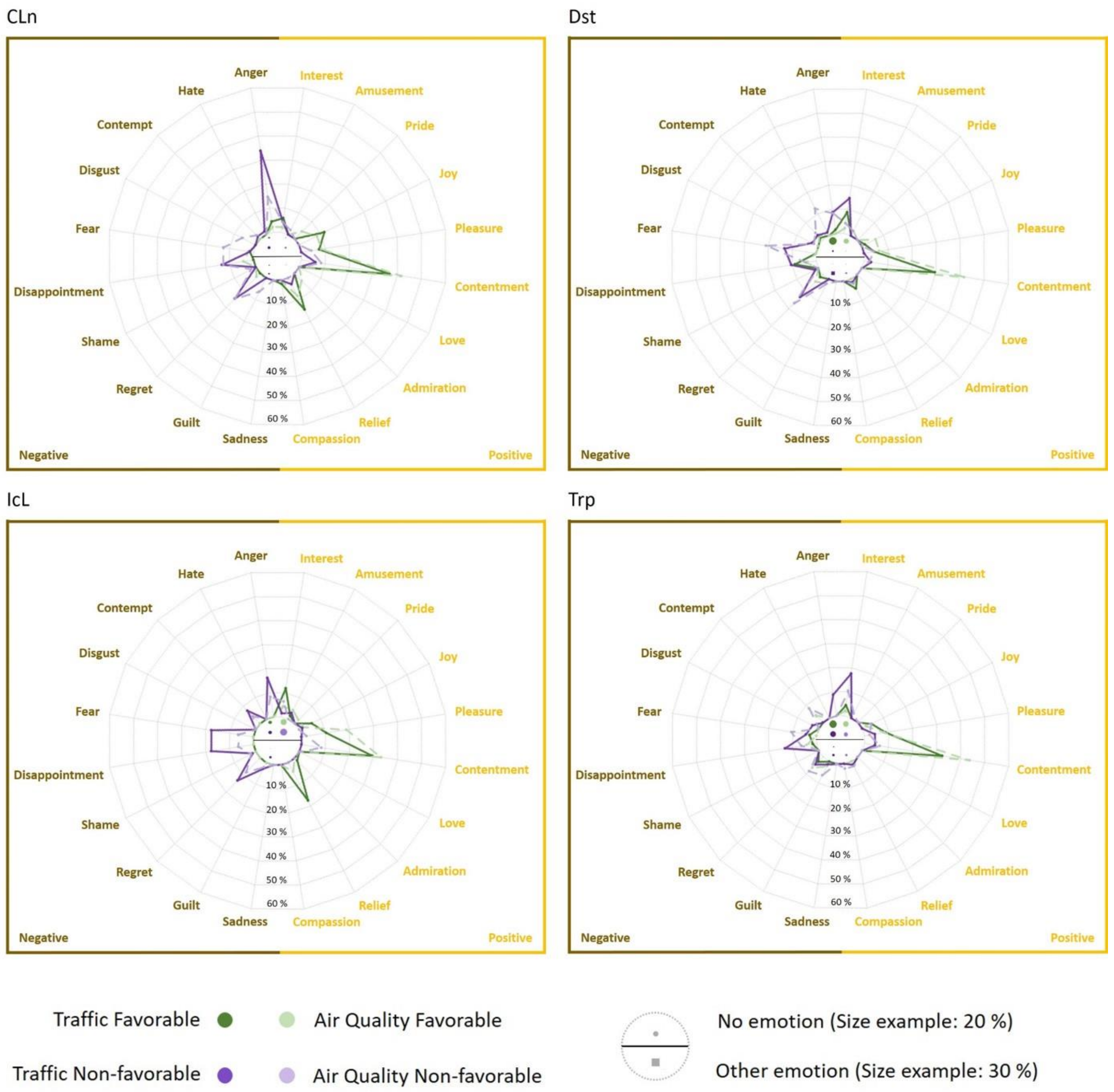


Figure 6.27: Spider charts for visualizing percentages of felt emotions in response to line type design variants.

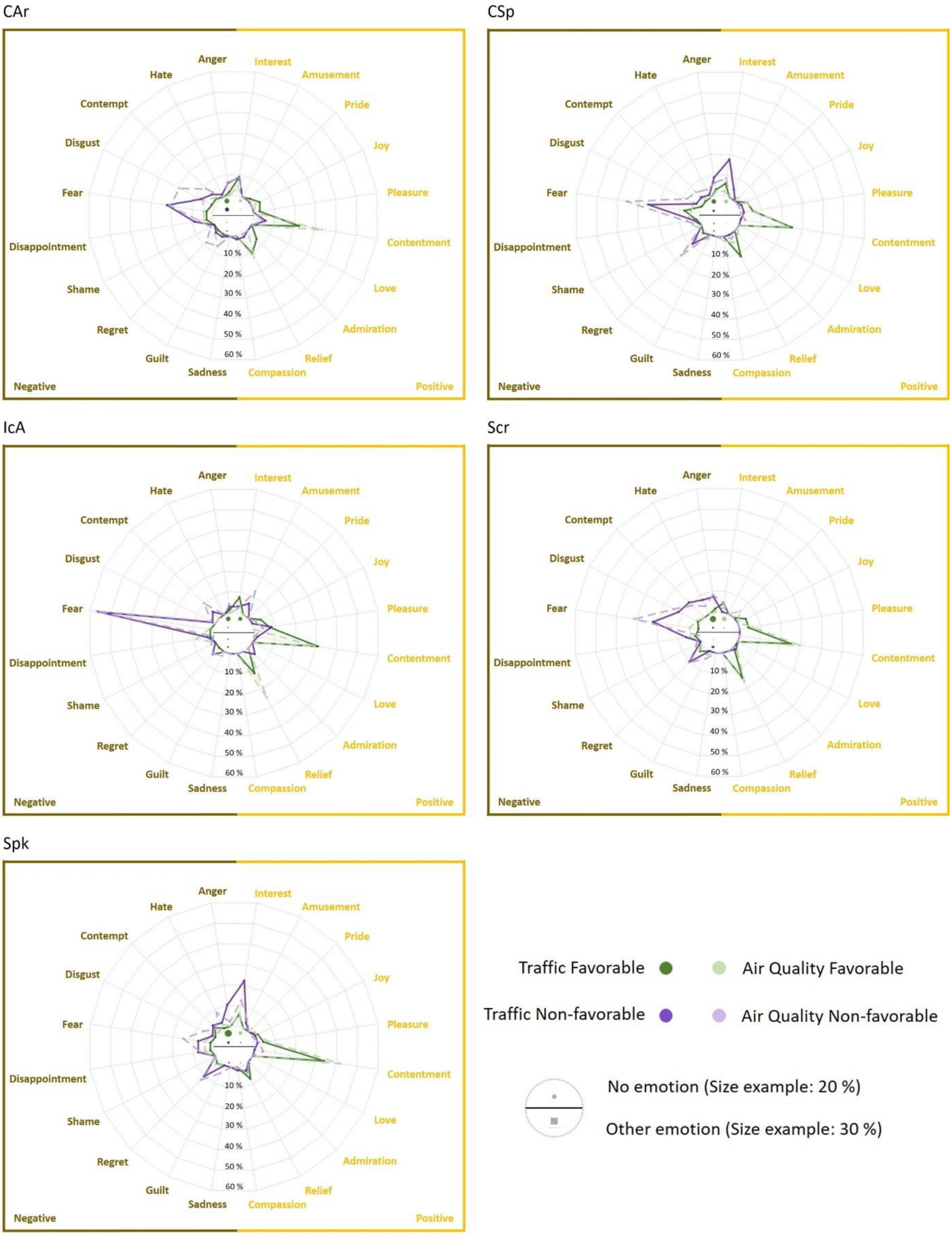


Figure 6.28: Spider charts for visualizing percentages of felt emotions in response to area type design variants.

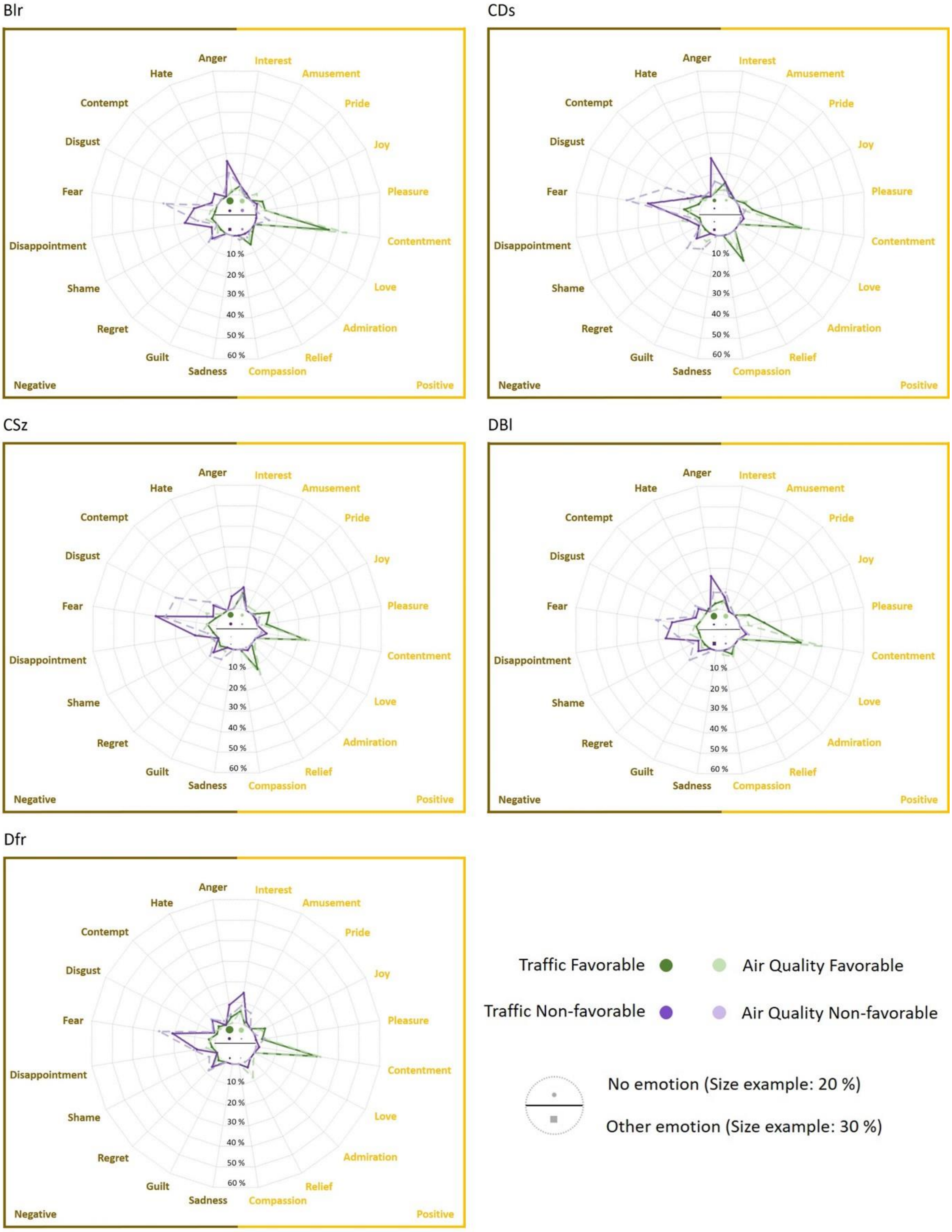


Figure 6.29: Spider charts for visualizing percentages of felt emotions in response to line + area type design variants.

6.3.6.6 H6: Effect of emotions on route choice decision making

It was hypothesized that there might be a relationship between participants' felt emotions and their route choice decisions (*H6*). Binary logistic regression was performed to assess whether the felt emotions related to the modified map visualizations significantly predict a route choice decision in favor of the *societally favorable* route.

Route choice values were recoded from the 1-5 scale to binary format, with value 1 indicating route choice in favor of the favorable route (original values 4 and 5) and the value 0 indicating route choice in favor of the non-favorable route or no preference (original values 1, 2 and 3). Additionally, the nominally scaled emotion variable with the characteristics *positive, negative, no* emotion, and *other* emotion has been coded as follows: While responses for no emotion have been coded as 0, negative emotions have been coded as values ranging from -1 to -5. For this, the value -1 has been multiplied with the value for the corresponding intensity of the emotion as indicated by the participant in the Geneva Emotion Wheel (ordinal values between 1 and 5). The same principle has been applied for positive emotions, resulting in values that range from 1 to 5, with the value 1 being multiplied with the intensity value of the emotion. Due to its limited informative value, responses for the option *other* emotion have not been considered as part of the model.

For most of the design variants, the model suggests that the emotions evoked by viewing the map representations have an impact on participants' route choice behavior. Table 6.10 summarizes the regression coefficients and odds ratios for the binary logistic regression model. For each design variant, the results are provided separately for the two scenarios and within each scenario, emotions related to the *societally favorable* route (*Fav*) and emotions related to the *societally non-favorable* route (*N_Fav*) are distinguished.

It can be observed that for the emotions related to the favorable route, in most cases, a route decision in favor of the favorable route is more likely if a positive emotion has been felt regarding the visualization of the favorable route (odds ratio > 1), while for the non-favorable route, this is more likely to occur in the case of a felt negative emotion (odds ratio < 1). However, there are some deviations from this pattern. While for the non-favorable route, in all cases, negative emotions are more likely to influence route choice in favor of the favorable route, there are some cases in which negative emotions for the favorable route influence route choice. This pattern is for example observable for the *Color Distortion* (*CDs*) variant in the *traffic* scenario (odds ratio = 0.939) and the *Color Size* (*CSz*) variant (odds ratio = 0.902) in the *air quality* scenario. Many of these cases relate to area modifications such as variants using a color background. As the analysis on emotions has shown, these types of visualizations evoke a variety of emotions and due to their areal nature, negative emotions may not only be associated with the non-favorable route but to some extent also with the favorable route.

In the *traffic* scenario, three relations have been found significant, while for the *air quality* scenario, six relations are significant. This indicates a slightly higher importance of emotions for making a route choice decision in the *air quality* scenario. Furthermore, significant relations have been primarily found for emotions related to the non-favorable route (seven relations), while for the favorable route, only two significant relations have been found. Supporting sub-hypothesis *H5*, this finding indicates that both positive and negative emotional responses to map visualizations can influence route choice. However, negative emotions related to non-favorable routes are more likely to influence route choice behavior than positive emotions related to favorable routes.

*Table 6.10: Test statistics for the binary logistic regression model including the regression coefficient (Reg Coef), the Odds Ratio (Exp(B)) and the p-value, * p <.05, ** p < .01. For each variant, statistics are provided for emotions related to the societally favorable route (Fav) and the societally non-favorable route (N_Fav).*

Variant	Traffic				Air Quality			
	Emotion_Route	*Reg Coef*	*Odds Ratio*	*p*	*Emotion_Route*	*Reg Coef*	*Odds Ratio*	*p*
Blr	Fav	.152	1.164	.289	Fav	-.13	.878	.505
	N_Fav	-.279	.757	.051	N_Fav	-.14	.869	.412
CAr	Fav	.139	1.149	.295	Fav	.103	1.108	.408
	N_Fav	-.264	.768	**.009****	N_Fav	-.174	.84	.147
CDs	Fav	-.063	.939	.717	Fav	.343	1.409	.365
	N_Fav	-.177	.838	.229	N_Fav	-.653	.52	**.042***
CLn	Fav	-.023	.977	.895	Fav	.023	1.023	.911
	N_Fav	-.231	.794	.105	N_Fav	-.357	.7	**.036***
CSp	Fav	.041	1.042	.768	Fav	.221	1.247	.165
	N_Fav	-.181	.834	.059	N_Fav	-.29	.748	**.035***
CSz	Fav	-.032	.968	.8	Fav	-.103	.902	.505
	N_Fav	-.269	.764	**.01***	N_Fav	-.186	.831	.156
DBl	Fav	-.1	.905	.606	Fav	-.038	.962	.837
	N_Fav	-.241	.786	.184	N_Fav	-.176	.839	.251
Dfr	Fav	.105	1.111	.513	Fav	.418	1.518	**.041***
	N_Fav	-.032	.968	.779	N_Fav	-.427	.652	**.013***
Dst	Fav	.005	1.005	.97	Fav	-.01	.99	.963
	N_Fav	-.063	.939	.611	N_Fav	-.316	.729	.067
IcA	Fav	-.011	.989	.954	Fav	-.048	.953	.816
	N_Fav	-.294	.746	**.019***	N_Fav	-.292	.747	.058
IcL	Fav	.108	1.114	.563	Fav	.502	1.652	.082
	N_Fav	-.216	.805	.244	N_Fav	-.309	.734	.222
Scr	Fav	.168	1.183	.178	Fav	.182	1.2	.211
	N_Fav	-.261	.771	.125	N_Fav	-.311	.733	.06
Spk	Fav	.222	1.249	.083	Fav	-.01	.99	.943
	N_Fav	-.152	.859	.15	N_Fav	-.225	.799	.065
Trp	Fav	.241	1.273	.065	Fav	.27	1.311	**.047***
	N_Fav	-.127	.88	.271	N_Fav	-.096	.909	.466

6.3.6.7 Helpfulness of map visualizations

Participants were further asked which map was most helpful for making their route decision. Here, the results are very clear for the *traffic* scenario, since 74 % mentioned the *Color Line* (*CLn*) variant. This is very likely because the use of colors based on the traffic light metaphor is widely used and commonly known for visualizing traffic congestion. For the *air quality* scenario, the majority of participants also named the *CLn* variant (39.6 %), but other variants like *Icons Area* (*IcA*, 17 %) were also mentioned relatively often.

Regarding the least helpful map, the decision was much less clear to the participants, and large differences can be observed between the scenarios. For example, the *IcA* variant does not seem to be helpful for many participants in either scenario, although it has been rated as helpful for the *air quality* scenario by a larger group of participants. For the *Deformation* (*Dfr*) and *Icons Line* (*IcL*) variants, the symbology seemed much less clear in the *air quality* scenario (each 22.6 %) than in the *traffic* scenario. On the other hand, the *Scribble* (*Scr*) variant was much less helpful when communicating traffic information (16.4 %) than air quality. Table 6.11 provides the percentages of participants naming the different design variants as the most helpful or the least helpful map for making route choice decisions.

Table 6.11: Percentages of participants who rated the different design variants as the most helpful or the least helpful map for making route choice decisions.

	Most helpful		**Least helpful**	
Variant	*Traffic*	*Air quality*	*Traffic*	*Air quality*
CLn	74	39.6	0	1.9
Dst	1.4	0	5.5	1.9
IcL	4.1	7.5	6.8	22.6
Trp	4.1	3.8	5.5	11.3
CAr	0	5.7	9.6	0
CSp	4.1	7.5	1.4	3.8
IcA	1.4	17	17.8	17
Scr	0	5.7	16.4	3.8
Spk	8.2	3.8	6.8	5.7
Blr	0	0	8.2	0
CDs	1.4	1.9	5.5	3.8
CSz	0	7.5	0	1.9
DBl	0	0	6.8	3.8
Dfr	0	0	6.8	22.6
None	1.4	0	2.7	0

6.3.6.8 Route choice strategies

In addition to the helpfulness of map visualizations, participants were further asked about their general strategies for making a route choice decision. Since the collected data on route choice strategies has been provided by participants in a free text format, statements have been categorized into different strategy types. After examining each of the statements individually, it turned out that each of them can be assigned to one out of three distinct categories of strategies: These are 1) route choice only according to personal preferences, 2) personal preference in the first part of the route choice task, influence by visualization in second part, and 3) unsure.

Statements related to *strategy 1* have in common that they either do not include a hint that the modified visualizations had an influence on route choice, or that it is specifically mentioned that the visual communication was not followed. Since in this group, the visual modification has not been considered as a reason for route choice, the mentioned route choice factors were solely based on individual preferences related to the (assumed) real-world characteristics of the route options. Results reveal a very diverse range of factors that participants considered as part of their route choice strategy. Besides selecting the shortest or fastest path, these factors further include for example a small number of turns, directness of the route, straight route segments and the characteristics of the built environment and surrounding road network. These factors are widely in common with previous research on driver's route choice factors (Papinski et al., 2009; Bailenson et al., 1998).

Statements related to *strategy 2* describe similar route choice factors for decision making regarding the non-modified maps, but explicitly mention that they applied a different strategy for the modified maps. It became apparent that participants in this group seemed to change their strategy from decision making based on individual preferences to a more social behavior. Various participants mentioned that, based on the visualization, they prefer taking a route that is visualized as safer, clearer or less threatening, or that they now intentionally chose the route with longer distance, since they wanted to avoid the affected areas. Strong visual modifications have often been perceived as a disturbance that has been rated as negative, and hence desired to be avoided.

Finally, *strategy 3* either includes statements showing that the person was not sure about the used strategy, or statements that were difficult to interpret due to missing information that allows it to assign a specific strategy.

For determining which statement belongs to which strategy, statements have been assigned to the different categories by two independent raters. Inter-rater reliability revealed a substantial agreement between the two raters, Kappa = 0.76 (Landis & Koch, 1977).

After agreeing on a rating for the few cases with disagreements among the raters, 19 statements are assigned to strategy 1, 103 statements to strategy 2, and 4 statements to strategy 3. Table 6.12 summarizes each three examples of typical statements for the three different categories of route choice strategies.

Table 6.12: Typical statements for the three different categories of route choice strategies (translated from German).

	Strategy 1	**Strategy 2**	**Strategy 3**
Example 1	“I chose the - from my point of view - shorter route, regardless of any visualizations.”	“In the case of very poor air quality, I chose the supposedly longer route despite longer travel times, as this [air quality] seems to be the more important criterion to me.”	"The better route option."
Example 2	“Visually shortest route, rather few turns.”	“Generally, I opted for the shortest option. However, when further attributes such as hazards or hilly roads were added, I usually instinctively chose the opposite.”	"Gut feeling."
Example 3	“In most cases, how I get from A to B the fastest (regardless of air quality/with as few left/right turns as possible).”	“Selection without additional information: supposedly shorter or easier routes. With additional information: Avoidance of supposed impairments/disturbances.”	"visualized"

6.3.6.9 Text-based sentiment analysis

The polarity of the emotions reported by participants for the favorable and the non-favorable route have further been compared to sentiments expressed in the free text task for describing helpfulness of map visualizations. For this purpose, a text-based sentiment analysis has been performed using two different tools. Since many of the free texts provided by participants were relatively short, the dataset was not found ideal for this type of analysis, simply due to the lack of words that can be included in the analysis. Examples of descriptions are sentences like “*The symbols on the map clearly and unmistakably indicate a danger, so that you decide against this route*”, but also quite short descriptions like “*Very clear representation of the traffic load*”.

The first tool is based on the *NRC Emotion Lexicon* (Mohammad & Turney, 2013). In the original version, this lexicon consists of a list of around 14000 English words and their association with eight emotions (*anger, fear, anticipation, trust, surprise, sadness, joy,* and *disgust*) and two sentiments (*negative* and *positive*). Due to differences in the used emotions terms compared to the *Geneva Emotion Wheel*, analysis has been limited to the distinction between the two sentiments. Furthermore, for enabling analysis using German language, the original Python tool has been adapted by linking it to a German translation of the *NRC Emotion Lexicon.* It was decided to use this tool, since it has the option for providing results related to emotion categories, as well as related to sentiments. Results of this tool are provided as counts of sentiment or emotion terms found in the provided text data. One drawback of using this tool is that negation words are not considered, and hence could lead to incorrect assignments to sentiments.

To account for this problem, an additional tool was tested. The selected tool uses the *TextBlob-de* python package, which is the German language adaption of the *TextBlob* package for natural language processing such as sentiment analysis. A major difference to the analysis using the *NRC* tool is that negations are partially taken into account, in case the negation term directly precedes the emotion term. Results are provided as polarity ranging from -1 (negative) to 1 (positive), with 0 relating to a neutral sentiment. Using this tool, results for sentiments for helpful maps on average show a positive polarity (M = .18), while sentiments for not helpful maps show a slightly negative polarity (M = -.08). However, it was observed that many of the provided text descriptions have not been assigned any emotion or sentiment.

For preparing a comparison between the results of the sentiment analysis with the reported felt emotions based on the Geneva Emotion Wheel, data has each been recoded to the same format using three different values. Accordingly, the value 1 relates to a positive sentiment or emotion, while the value -1 relates to a negative sentiment or emotion. The value 0 relates to either no emotion or a neutral sentiment.

A comparison between the two methods shows that both tools provided partly similar results. A chi-squared test confirmed that there is a significant relation between the results provided by the *NRC* and the *TextBlob* tool considering descriptions for the helpful maps (X^2 (4, N = 105) = 26.53, p = < .001), but for the not helpful maps no significant relation has been found.

Results further reveal that the percentage of matching between felt emotions and sentiments from the text descriptions is relatively low. Table 6.13 summarizes the percentages of matching between the results of the two sentiment analysis tools and the reported emotions. As expected, a comparatively high percentage of matching is reached by comparing the sentiment results for the helpful map (abbreviation *h*) with the emotion for the corresponding favorable route for both tools. Similar results can be observed for the comparison between not helpful maps (abbreviation *nh*) and emotions related to the non-favorable route. However, surprisingly, the comparison between not helpful maps and the favorable route reached a similar level of matching, which might be due to a relatively high number of neutral sentiments and no emotions. However, none of these relations reached statistical significance, indicating that sentiments could not be estimated reliably based on the provided text material.

Table 6.13: Matching of sentiment polarity between text descriptions and reported felt emotions in percent.

	Emotion_favorable	Emotion_non_favorable
NRC_h	38.83	23.76
NRC_nh	39.78	34.44
TextBlob_h	39.6	24.24
TextBlob_nh	32.26	32.22

6.3.6.10 *Suitability of visualizations*

Figure 6.30 provides the results for the suitability ranking of the different design variants based on the percentages of assigned ranks. Results for the suitability of design variants are shown in descending order, based on ranks 1 and 2 in the *traffic* scenario.

In general, the pattern is consistent with the route choice results, and widely agrees with the results for suitability estimation for communicating air quality information as described in user study 1 (chapter 6.1.4). The *Color Line* (*CLn*) variant, for example, is rated as suitable for the *traffic* scenario, but comparatively less suitable for visualizing *air quality* information. The *Icons Line* (*IcL*) variant is another line type modification that has been found relatively suitable for visually communicating *traffic* information. While there is a clear favorite for the *traffic* scenario, the most suitable representation for *air quality* is less clear. Although the *CLn* variant was on average also rated as most suitable for visually communicating *air quality*, there is a tendency for variants using areal modifications being rated as more suitable for communicating the *air quality* scenario than line type modifications – such as the color-based variants (*CAr*, *CSz*, *CSp* and *CDs*) and the *Scribble* (*Scr*) variant.

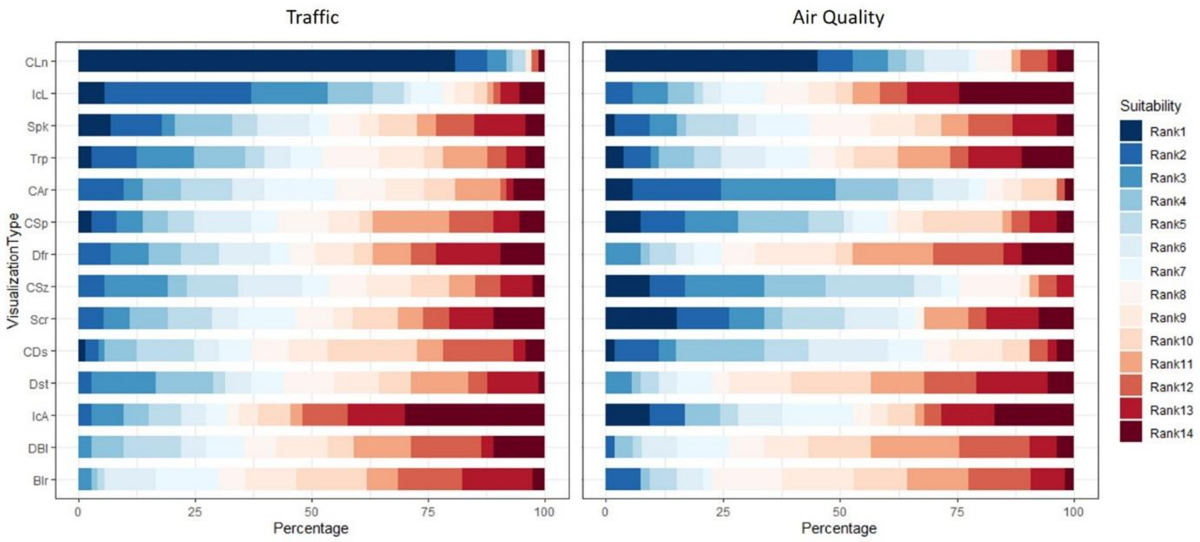


Figure 6.30: Stacked bar charts illustrating the percentages of ranks assigned to design variants for estimating suitability of visualizations for communicating the scenarios traffic or air quality. Rank 1 indicates the highest suitability, Rank 14 the lowest.

6.3.6.11 *Further factors influencing route choice*

To conclude the analysis of the user study results, a possible influence of gender, as well as map usage on route choice, has been examined.

To test whether gender has an influence on route choice, ordinal regression has been performed, with *gender* and *design variant* as independent variables, and *route choice* as the dependent variable. Due to the very low number of participants in the groups *diverse* and *not specified*, the sample size was insufficient to compare these groups.

While *design variant* has a significant effect on route choice (X^2 (13, N = 126) = 196.16, p = < 2e-16), the influence of *gender* was not significant (X^2 (1, N = 126) = .001, p = .97). Similarly, the interaction between *design variant* and *gender* was not significant (X^2 (13, N = 126) = 13.27, p = .43). This indicates that the differences in route choice behavior among the different design variants do not depend on gender. A further tested interaction between *scenario* (X^2 (1, N = 126) = .81, p = .37) and *gender* (X^2 (1, N = 126) = .02, p = .89) when making route choice decisions also was not significant (X^2 (1, N = 126) = 1.99, p = .16).

Similarly, an ordinal regression model using *map use experience* and *design variant* as independent variables revealed no statistically significant differences in route choice among participants with different levels of *map* *use experience* (X^2 (3, *N* = 126) = 4.7, *p* = .2), but did identify significant differences among *design variants* (X^2 (13, *N* = 126) = 196.19, *p* = < 2e-16). Also, the interaction between *design variant* and *map use experience* was not significant (X^2 (39, *N* = 126) = 20.87, *p* = .99). A further tested interaction between *scenario* (X^2 (1, *N* = 126) = .59, *p* = .44) and *map use experience* (X^2 (3, *N* = 126) = 4.46, *p* = .22) was also not significant (X^2 (3, *N* = 126) = .16, *p* = .98). This indicates that for most of the design variants, the likelihood of being influenced by the symbolization method does not depend on the level of experience in map usage and map reading. Therefore, the applied visual communication seems to work as desired for a range of types of users.

6.3.7 Discussion – User study 3

The results of the user study have shown that the most appropriate design decision for nudging a traveler's route choice towards a *societally favorable* route varies depending on the phenomenon that is communicated. Furthermore, different types of symbolization evoke different emotions that in some cases seem to contribute to decision making. The findings of this user study demonstrate the importance of appealing to people's emotions related to the communicated situation for achieving a behavior change in route choice (Roeser, 2012), by applying suitable map symbolization.

The findings are discussed with a focus on the influence of different design variants on route choice and the effects of emotions on route choice. In this context, it is discussed to which extent the six sub-hypotheses could be supported by the results of the user study. The section concludes with some limitations of the study design and an outlook for future research directions.

6.3.7.1 Influence of different design variants on route choice

The route choice models supported the sub-hypothesis (*H1*) that the map-reader's route choice decision can be influenced towards choosing a *societally favorable* route for all design variants (Fuest et al., 2021). Although the route maps have been prepared using slightly stricter design specifications than for the maps prepared for user study 2, the results show a similar effect of using map symbols on route choice behavior in both user studies. This indicates that people may focus more on the visualizations added to the map than on the structural characteristics of the maps, when making their decision.

The fact that *scenario* was not a significant factor in this model leads to reject the sub-hypothesis (*H2*) that participants would exhibit a higher willingness for showing pro-social behavior in the *traffic* scenario than in the *air quality* scenario. Different than suggested by Roeser (2012), participants seemed to feel affected by the introduced environmental impact, since this study has shown that environmental issues such as air pollution motivated people to a similar extent to choose a *societally favorable* route as did disruptions in traffic conditions. As Banks and collaborators (1995) suggest, these results further verify the effectiveness of the applied loss framing for evoking a behavior change, related to scenarios that are considered risky or potentially hazardous for the population. The emotions evoked by the map symbolization may also have motivated a change in environmental behavior (Roeser, 2012).

Rather, the results suggest that participants' willingness to follow the route recommendation depends more heavily on the visualization chosen for the particular scenario. In the following, the performance of several design variants is discussed that yielded particularly interesting or surprising results.

As hypothesized in *H3*, the results of the user study have shown that line type visualizations were most effective for the *traffic* scenario, while in the *air quality* scenario, areal symbols were more effective. In the *air quality* scenario, it was also found that variants using a color area background are effective for symbolizing emissions. Hence, results verified that choosing commonly applied types of visualization for the two scenarios (Kubíček et al., 2017; Lahr & Kooistra, 2010) also leads to a higher effectiveness for influencing route choice. Although it was rated as suitable for communicating air quality information, the *Color Area* (*CAr*) variant was less effective for influencing route choice than the areal symbol combined with additional visual variables, the most effective of which was the *Color Distortion* (*CDs*) variant, which visualizes the non-favorable route as a distorted line (*H4*). Since the results for the *CDs* variant also show a high proportion of negative emotions evoked for the non-favorable route, it seems that more distinct types of symbolization that potentially evoke strong emotions may be more successful for achieving a behavior change. In general, it was found that combinations of several visual variables, such as those involving colors, might be beneficial for some design variants to strengthen the graphic encoding of the visualized attribute (Roth, 2017), while for other variants, combinations are less useful.

The results also showed that the *Color Line* (*CLn*) variant, which is widely known and used for depicting traffic data, has performed well for influencing route choice in the *traffic* scenario. Although this variant also performed reasonably well in the *air quality* scenario, there are clear differences in its effectiveness, but particularly in its suitability and helpfulness between the scenarios. The still relatively good performance of the *CLn* variant for the *air quality* scenario could be explained by the fact that symbolization using colored lines is a very common type of visualization in route maps that might still be reasonable and understandable to some extent, despite its atypical application to an 'areal' scenario.

The results for the *Icons Area* (*IcA*) variant are somewhat surprising. Despite the low suitability rating of this variant for communicating favorability of routes and the comparatively low scoring of helpfulness for making a route choice decision, this variant was in fact effective for influencing route choice. Additionally, this variant evoked strong emotions such as fear for the societally non-favorable route, indicating it is a very emotive symbolization method. The effectiveness of icons for conveying the seriousness of the communicated situation has also been verified by Pirani and collaborators (2020). This clear contradiction between effectiveness and rated suitability and helpfulness suggests this type of visualization might be very controversial, which therefore may not make it appropriate for universal usage. The effectiveness and suitability of this design variant may vary depending on the choice of the icon. As reported by participants in their free text comments, using skull icons may be too drastic; others had difficulties taking the visualization seriously. Therefore, a different icon choice may lead to markedly different results.

The results based on pairwise comparisons between the different design variants further suggest that the variant *Transparency* (*Trp*) performs differently from most other variants. In particular, its effectiveness was low for both scenarios. The felt emotions results further indicate that due to the high percentage of participants selecting the emotion *interest* for the societally non-favorable route, the symbolization might be ambiguous for some map users. Given its relatively low suitability and helpfulness ratings, it can be concluded that the variant *Trp*, at least as it has been operationalized, was not successful for influencing route choice. Interestingly, the *Trp* variant as used in this study visually resembles the *noise* variant as presented in Carroll et al. (2020), which they found to be effective for emotionally influencing the user's choice of the optimal path. The low effectiveness of using transparency for symbolizing route options in this study might be related to difficulties in associating the symbolization with the two scenarios.

6.3.7.2 The effect of emotions on route choice

The emotions that participants felt were consistent with the sub-hypothesis (*H5*). Routes communicated as favorable primarily evoked positive emotions, while routes communicated as non-favorable primarily evoked negative emotions. Consistent with previous research (Kelly, 2019), the findings indicated that color in general has a great impact on emotional responses, particularly in the *air quality* scenario. Similar to their effectiveness for influencing route choice, it can particularly be observed that the variants that use a color area background evoke negative emotions among a high percentage of participants, which also influenced the emotions felt concerning the *societally favorable* route in the map towards a more negative emotion. Furthermore, in the *air quality* scenario, negative emotions have generally been evoked more frequently than in the *traffic* scenario, which indicates that negative consequences related to this type of environmental information seem to play a more important role in decision making than for the *traffic* scenario.

Surprisingly, for some design variants (particularly *Transparency* (*Trp*) and *Spikes* (*Spk*)), participants felt positive emotions for the route that was visually communicated as non-favorable. Taking a closer look at the specific emotions felt for these variants, it becomes apparent that the positive emotion *interest* was felt by many participants for the non-favorable route. Considering the relatively low effectiveness of the design variants *Spk* and particularly *Trp*, this further raises the question, whether interest in the route visualization might be related to uncertainty about the information that is communicated by the visualization.

Negative emotions towards the societally non-favorable route are more likely to affect route choice behavior than positive emotions towards the favorable route (*H6*). This pattern was observed to a greater degree in the *air quality* scenario. Considering the higher level of negative emotions felt for the maps depicting *air quality*, negative emotions associated with environmental issues such as air pollution indeed seem to have evoked a behavior change towards a more *societally favorable* route choice decision. Hence, different than suggested by Pirani and collaborators (2020), participants reported relatively strong emotional responses to a seemingly distant topic such as air pollution. In particular, the application of framing in the context of map symbolization might have helped presenting this kind of topic as an emotionally closer issue (Spence & Pidgeon, 2010). However, the larger impact of negative emotions towards the non-favorable route on choosing the favorable route might be biased due to the decision to primarily visually modify non-favorable routes, while the favorable route remained unmodified, except in cases where there are symbols in close proximity to the favorable route.

6.3.7.3 Limitations of the study design

The routes that were selected for the user study have a length between 3.5 and 7.5 kilometers, which should correspond to typical inner-city traffic (e.g. for running errands). Therefore, longer route lengths were not considered. However, it is likely that people make different choices depending on the length of a route. For example, for longer, between-city routes, it is likely that there are fewer possible route options available, which, however, involve more different road types (such as highways or country roads). Also, the driver behavior may differ for different travel purposes, such as commutes or running errands, since factors such as time pressure might be of different importance.

Although the user study was prepared carefully to try to reduce potential sources of bias, based on comments collected from the participants regarding the study, a few issues were noticed that may have influenced the results to some extent. For example, some participants mentioned being unsure about interpreting some of the symbolization types, while others indicated they had difficulties expressing emotions related to a map in general. This difficulty might have arisen because it was asked for their *anticipated emotions*, instead of measuring actual emotions felt while exposing participants to the traffic or air quality situation.

A further limitation has been observed related to the free text descriptions provided by participants for describing their route choice strategies and the reasons why a map symbol has been estimated as helpful for making a decision or not. A sentiment analysis was performed using emotion lexicons for analyzing the amount of emotion words included in a textual description. This method requires long enough text as an input, in order to provide meaningful results. However, since most participants provided rather short descriptions, the data in general was found not sufficient for performing this type of analysis. It is assumed that, due to the impersonal online setup, it is difficult to capture participants' felt emotions, and because of the length of the survey, participants may have felt less motivated to provide detailed descriptions. Therefore, it is suggested that online surveys are only conditionally suitable for collecting textual or verbal descriptions for analyzing emotions, while a personal interview between the experimenter and the participant might yield more useful results. Another option for possibly obtaining more useful results could be to design a similar user study that, however, focuses on collecting textual descriptions only, which might help the participant putting more effort in providing such descriptions. Yet another possibility would be to more directly ask for describing emotions that participants possibly have felt.

A further potential issue might be that the *Geneva Emotion Wheel* may not contain all relevant emotion terms related to this task. Participants suggested that some of the emotion terms such as *love* or *sadness* may not be appropriate in the context of route choice. They also mentioned that emotions such as *confusion, uncertainty, annoyance, stress*, or *boredom* could be considered when measuring emotions related to route maps. Furthermore, some participants mentioned that they felt multiple or mixed emotions, which may have impeded choosing one specific emotion term on the wheel.

6.3.7.4 Outlook

Since emotions related to route maps have been found to play an important role in route choice decision making, it is planned to conduct further research that investigates the effectiveness of other means of evoking emotions in route maps. In this context, textual descriptions, sonification using audio cues (Edsall, 2010), or animations are potential approaches that could enhance effectiveness for influencing route choice by intensifying emotional responses.

Furthermore, since the results showed that design variants differed in their effectiveness for influencing route choice and felt emotions depending on the scenario, additional scenarios could be studied with the aim to recommend *societally favorable* routes. This may also involve the generation of further design variants that could be potentially useful for symbolizing a specific scenario.

6.3.8 Conclusion – User study 3

In this study, it was investigated how emotional responses to cartographic symbols can influence a traveler's route choice decision towards choosing a route option that is favorable from a societal point of view. The results of the user study verify the effectiveness of visual communication for influencing route choice using map symbols for the two tested scenarios *traffic* and *air quality*. Figure 6.31 provides a visual overview of the overall performance of the tested design variants regarding the different tested aspects *route choice*, *shift*, *combinations*, *emotions*, *helpfulness*, and *suitability*.

Variant	Scenario	Route choice	Shift	Combinations	Emotions	Helpfulness	Suitability
CLn	Traffic	↑	↑	-	→	↑	↑
	AQ	↗	↗	-	↗	↗	↑
Dst	Traffic	↗	↗	-	→	→	→
	AQ	↗	↗	-	→	→	↘
IcL	Traffic	↑	→	-	→	→	↗
	AQ	↗	→	-	→	↘	↘
Trp	Traffic	↘	→	-	→	→	→
	AQ	↘	→	-	↗	↘	↘
CAr	Traffic	↘	↘	-	↑	→	→
	AQ	→	→	-	→	→	↗
CSp	Traffic	↗	↗	↗	→	→	→
	AQ	↗	↗	↗	↗	→	↗
IcA	Traffic	↑	↗	-	↗	↘	↓
	AQ	↑	→	-	→	→	→
Scr	Traffic	→	↗	-	→	↘	→
	AQ	→	↗	-	→	→	↗
Spk	Traffic	→	↗	-	→	→	→
	AQ	→	→	-	→	→	→
Blr	Traffic	↘	→	-	→	→	↘
	AQ	→	↗	-	→	→	↘
CDs	Traffic	↑	↗	↑	→	→	→
	AQ	↑	↗	↑	↗	→	↗
CSz	Traffic	→	→	→	↗	→	→
	AQ	→	↗	→	→	→	↗
DBI	Traffic	↗	↑	→	→	→	↘
	AQ	→	↗	→	→	→	↘
Dfr	Traffic	↗	↗	-	→	→	→
	AQ	→	↗	-	↗	↘	↘

↑ Very good ↗ Rather good → Neutral ↘ Rather poor ↓ Very poor

Figure 6.31: Qualitative evaluation of the performance of the tested design variants concerning different aspects. AQ = Air quality.

Regarding the aspect *combinations*, only those design variants are evaluated that combine multiple visual variables in one representation, while regarding the aspect *emotions*, the assessment is made based on the results from the binary logistic regression model. The performance of a variant is evaluated as “good” in this aspect, in case a significant influence has been found. Otherwise, the variant is evaluated as neutral.

Results have shown that most effective use of symbolization differs depending on the scenario. In general, visualizations that only modify lines were more effective in the *traffic* scenario, while areal modifications were more effective for the *air quality* scenario.

For the *traffic* scenario, the *Color Line* (*CLn*) variant, which is widely used for visualizing traffic information, seems to be an appropriate design choice based on several factors such as effectiveness, suitability, and helpfulness for decision making. Another variant that seems appropriate for communicating traffic information is the variant *Icons Line* (*IcL*), which uses symbols for communicating *societally favorable* and *non-favorable* parts of the route.

Although the *Color Line* (*CLn*) variant also performed reasonably well in the *air quality* scenario, in general, the variants using a color area background (*CAr, CSp, CSz* and *CDs*) seem appropriate design choices for communicating air quality levels. While the *Color Area* (*CAr*) variant seems less effective on its own, its effectiveness increases when an additional visual variable was added to the color area representation – with the *CDs* variant performing best among the tested variants when communicating air quality.

Furthermore, this study has shown that the different design variants have evoked a wide range of emotions in participants. While non-favorable routes mainly evoke negative emotions (particularly *fear*), *societally favorable* routes mainly evoke positive emotions (particularly *contentment*) or no emotions. If the *air quality* scenario is introduced, the visualizations evoke a higher percentage of negative emotions as compared to the *traffic* scenario. Using binary logistic regression, it was further shown that for some of the design variants, positive or negative emotions as a response to the map visualizations contributed significantly to changing the route choice decision in favor of the *societally favorable* route option. The map design rated by participants as *most suitable* seems very clear for the *traffic* scenario (*Color Line* variant), but less clear for the *air quality* scenario. In general, it was observed that areal modifications seem more suitable for the *air quality* scenario, while line modifications seem more suitable for the *traffic* scenario.

7 Interactive web-based visualization of route maps

The previously described user study results verify the effectiveness of using cartographic symbolization for nudging a traveler's route choice towards choosing a *societally favorable* route. Hence, based on these findings, an interactive, web-based visualization of route maps has been realized. To achieve this, a prototype version of a routing application has been implemented, which, for a specified start and destination location, not only calculates and visualizes an *individually efficient* route option, but – if available – also a *societally favorable* route. According to its purpose of recommending social routes, the routing application is named "SocialRoutes – The *Social* Routing Application".

In this chapter, the architecture and the user interface with the main functionalities of the application are presented, followed by an evaluation of the usability and user-friendliness of the application. Finally, some limitations of the currently implemented prototype version are discussed and future adaptions of the application architecture and design are proposed.

7.1 Application architecture

In the following, the architecture of the routing application is described. Figure 7.1 illustrates how the different components are interrelated with each other. The developed routing application consists of a typical client-server architecture. This means that the client sends a HTTP request to the server, which evaluates the request and then sends a HTTP response back to the client.

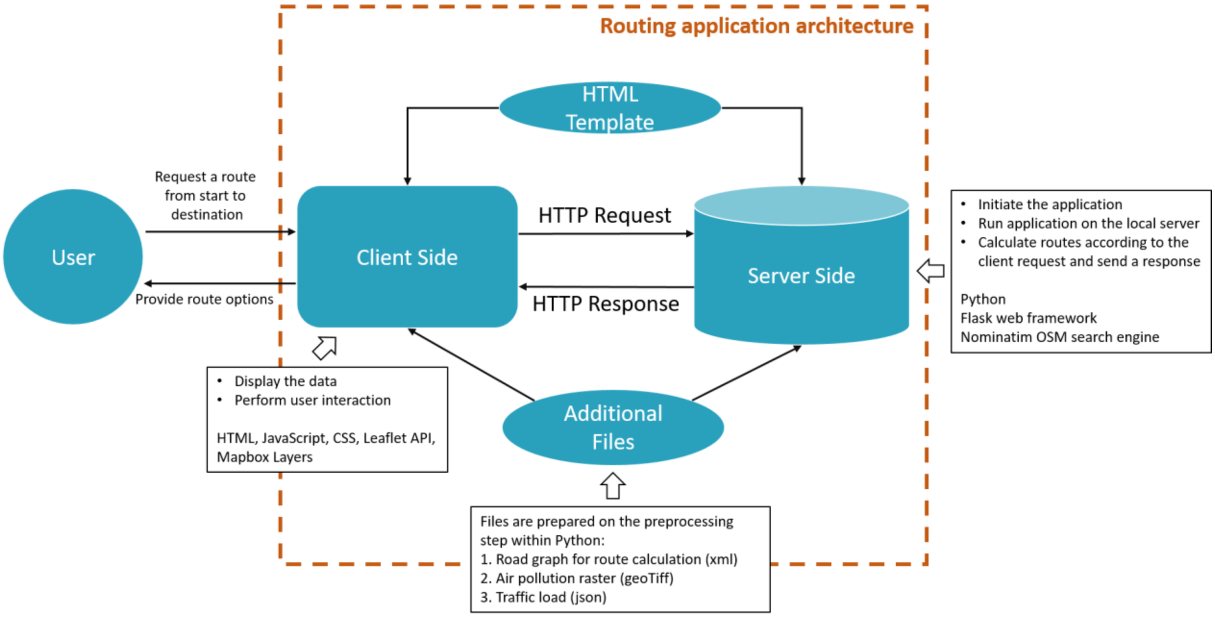


Figure 7.1: Routing application architecture.

The process is initialized by the user requesting a route from the start to the destination location according to individual preferences and concludes by providing the route options to the user. The client side is responsible for displaying the data and performing user interactions. On the client side, the following components are used: HTML, JavaScript, CSS, Leaflet API and Mapbox Layers. HTML is primarily used for creating the content of the web page that is visible for the user. JavaScript is used to add interactive content to the application user interface, such as switching between different visualization types or adding different map layers. CSS is used for defining the design and styles of the elements of the user interface, such as checkboxes, buttons or background colors. Furthermore, Leaflet API is used for visualizing geographic information for the background map layer, while the different types of base maps are retrieved using Mapbox Layers.

The server side is responsible for initiating the application, running the application on the local server and calculating routes according to the client request, and sending a response. On the server side, the following components are used: Python, *Flask* web framework, and the *OpenStreetMap* search engine *Nominatim*. Among others, the programming language Python is used for implementing the routing, the interpolation of values of the measured phenomenon and assignment of this information to the road graph, as well as for functions for performing the cartographic generalization. The source code of the application provides the option to choose between three different interpolation types (linear, nearest neighbor, and inverse distance weighting (IDW)), while in the current version of the application, IDW interpolation is applied (with values rounded to two decimal places after a comma). This decision has been made, because IDW yielded the best interpolation results in terms of simulating a realistic data distribution.

The local server used for the application is created using the python-based web framework *Flask*, which communicates via the Web Server Gateway Interface (WSGI). An advantage of using this framework for web application development is the uncomplicated integration of existing libraries for adding functionalities. The *OpenStreetMap* search engine *Nominatim*, however, runs on a separate server that performs OSM search. For the application, it is used in the context of searching for places by typing a location for the purpose of defining the start and destination location of a route. The search is requested with JavaScript by using XMLhttpRequest and response via specified URL to the *Nominatim* site (https://nominatim.openstreetmap.org/ui/search.html).

A HTML template is used for defining the design of the web page that features the application. Hence, it communicates with both the client and server side of the application. For the current prototype, some additional files are used, which are prepared on a preprocessing step using Python. This includes a road graph for the calculation of the route, which is prepared in .xml format, an air pollution raster prepared as .geoTIFF and a traffic load road network file in .json format. The .geoTIFF and .json files are used for providing a visual overlay of the air pollution or traffic information.

The road network information is retrieved from the *OpenStreetMap* (*OSM*) database using the Python package OSMnx. The package supports downloading routable road networks and also includes the option to visualize and analyze geospatial data. The amount of the requested data can be filtered by location, such as by using a bounding box, address or the name of a city. Consequently, geospatial data within the boundaries of the requested area is provided. Moreover, it is possible to request road networks for different modes of transport, including driving, walking and cycling. Hence, only those geospatial objects are extracted, which are relevant for the chosen mode of transport. For the application, a road network of the type ‘drive’ is requested, which comprises only drivable public roads. The weighted road graph used for this application is created using OSMnx. Weights are assigned both for the calculation of the fast and the social route.

7.2 User interface and functionalities

The user interface of the routing application provides several functionalities, while still featuring an overall clean and simple design. Figure 7.2 illustrates a screenshot of the user interface of the application in its default view when accessing the web page.

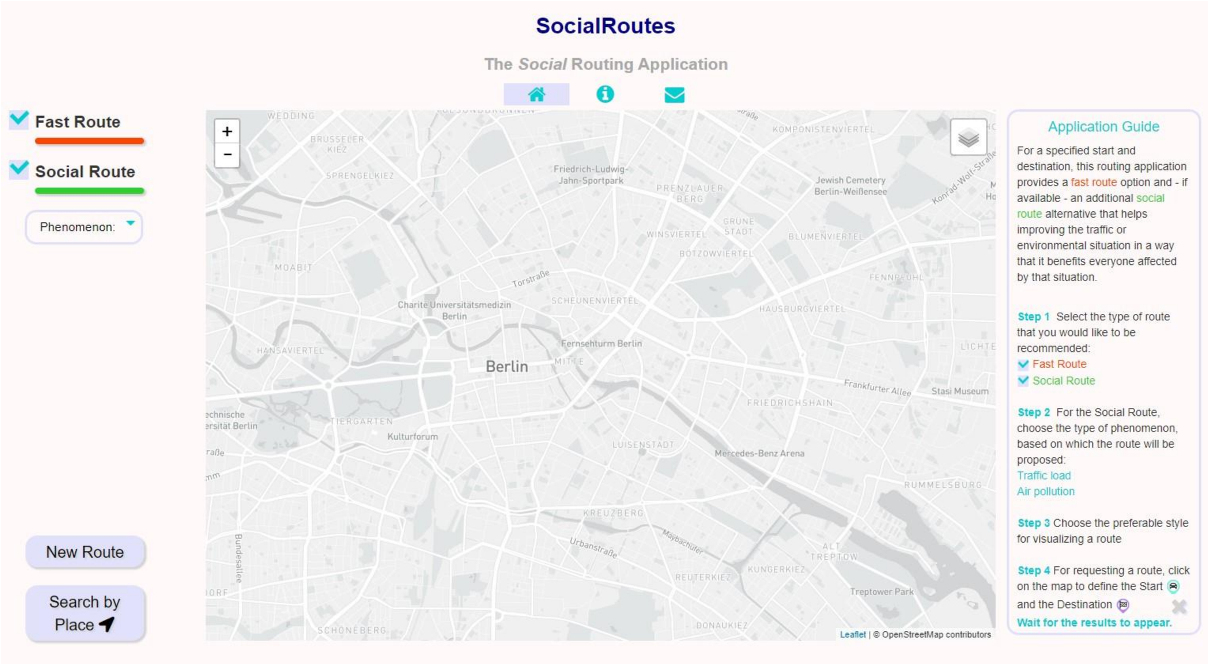


Figure 7.2: Default view of the routing application's user interface.

The default view involves several different components. The central part of the user interface shows a base map layer, which has three main functions: 1) providing a general overview of the spatial location, 2) selection of the start and end point of a route, and 3) visualization of route options on top of the base map. The map section that is shown to the user can be changed by zooming and panning. The zoom function can be either performed using the mouse wheel, or by pressing the '+' button for zooming in or the '–' button for zooming out. In the default view, the prototype version of the application is centered at the inner city of Berlin.

On the right side next to the map, a static application guide provides step-by-step instructions for explaining the usage of the routing application. The text box showing this information can be closed, in case it is not needed, while the map section is then extended to the right. Most of the functionalities for user interaction are located on the left side next to the map, including the selection of the route type, the type of environmental impact, the symbolization type and the option to calculate a new route. The title of the application and three buttons cover the space above the map, namely the *home* button, an *information* button and a *contact* button. The *home* button is activated by default. Hence, the default view of the start page is shown. The *information* button is used for making the application guide re-appear, in case it has been closed before. The contact button provides a shortcut to the email program of the user, and therefore facilitates to contact the maintainer of the application.

The terms and descriptions used in the routing application are intentionally kept simple, so that users without any cartography or traffic engineering related background could intuitively use the application. This also means that some of the terms used earlier in this thesis were replaced by a "simpler" term, such as using *social route* instead of *societally favorable route*, while still referring to the same principle.

The following main functionalities are provided to the user of the routing application:

A) Change base map layer
B) Select route type
C) Select environmental impact
D) Select route visualization style
E) Change visibility of the areal overlay
F) Select start and destination location for calculating a route
G) Initiate calculation of a new route
H) Search location by place, address or coordinates
I) Retrieve detail information about a route

A) The selection of the base map layer (referred to as *routing map*) can be changed by hovering over the corresponding layer icon. There are two possible options: A grayscale *routing map* and a color *routing map*. By default, a grayscale *routing map* is rendered. This type of map is suggested to be most suitable when colorful map symbols are visualized on top of the base map. In case the user prefers, the rendering of the *routing map* can be changed to a color version.

B) The application provides the option to calculate and visualize two different types of routes, as explained earlier in chapter 4.3.2 of this thesis: A *fast route*, which is introduced as the *individually efficient* route option, and an alternative *social route* option. This type of route is earlier referred to as the *societally favorable* route that is proposed to improve traffic depending on the impact of an environmental phenomenon. The user has the option to request only the fast route, only the social route, or both route options at the same time. For facilitating to distinguish both route types, different colors are used: Red color is used for the fast route and green color is used for the social route. This color coding is used for all types of visualizations, except those involving variations in color.

C) In case the calculation of the social route is requested, the type of environmental impact (referred to as *phenomenon*) needs to be chosen. The prototype version of the routing application currently provides a choice between the two options *traffic load* and *air quality*, which can be selected from a dropdown menu. The selected type of environmental phenomenon also influences the route calculation and visualization, since the defined thresholds may differ from each other.

D) Once the type of impact is selected, the options for choosing the route style are made visible to the user. The options are only shown after selecting a phenomenon, because the available route styles may vary depending on the phenomenon. The available route visualization styles cover a variety of design variants that have been found successful in this research – based on different criteria. For the phenomena *traffic load* and *air quality*, route visualization style options include the design variants *Distortion, Line Width, Color value, Color hue, Icons* and *Transparency*. By default, the option *None* is selected, which means that routes are visualized without using visual variables for showing variations in favorability of the routes. Once a route style different from the option *None* is chosen, a legend appears in the lower right corner of the base map, explaining the graphical differences in symbolization.

E) The user interface provides the option to visualize an areal overlay of the distribution of the underlying data related to the selected environmental impact. This may provide a better understanding of the severity of the observed impact and also may support the understanding of the route visualization. In case of *traffic load*, the visualization shows the variations in traffic load mapped to the road network, using a color scale from blue (low traffic load) to dark red (high traffic load). The provided values describe for each road segment the cars per hour, divided by 10. In case of *air quality*, the pollution visualization is realized by an areal overlay of interpolated PM10 values. The same color coding is used as for the *traffic load* scenario.

F) For requesting a route, the user is asked to click on the map to define the *start* (first click) and the *destination* (second click) location. After each click, an icon will appear at the corresponding location (a *car* icon for the *start* and a *flag* icon for the *destination*). Once both clicks have been made, the application internally initializes the automatic route calculation and visualization procedure, so that after a short time, the routing results will be visualized on the map. In case the user wishes to change the position of either the start or the destination location, it is possible to drag the icons to a different location. Hence, the route calculation will be adapted accordingly for the new *start* and *destination*. In a finalized version of the application, there should also be an option to get the start location by retrieving the GPS position of the user, which may facilitate the routing procedure and make it more intuitive.

G) The button *New Route* clears the currently visualized route, so that a new route calculation can be initialized as explained above.

H) The button *Search by Place* provides an alternative way for specifying the start and destination location, by manually typing a place, address, coordinates, instead of clicking on the map for choosing the *start* and *destination* of the route. As for all buttons in the application, further supporting information is displayed when hovering over the button. The list of geographical names uses the OSM search engine *Nominatim*. When typing a word, it autocompletes by proposing three options that are logically closest to the input. The proposed options can be selected by clicking on them. Route calculation is then initiated by pressing the *Get Route* button located on the right side next to the search mask for the start and destination. Once the route is calculated, the map is zoomed in or out to show the full spatial extent of the requested route. Additionally, the map window is resized automatically after pressing *Get Route* for a better overview of the mapped area. The search mask can be closed by pressing an *X* symbol located on the right side of the *Get Route* button.

I) When hovering over the route visualization, detail information concerning the position along the route is provided in a popup window. For any location along the route, this information includes the travel distance between the start and destination, the estimated travel time in hours and minutes, the observed value of the measured phenomenon, as well as the overall minimum and maximum observed values for the entire route. In case the routing result provides a fast and a social route, two separate popup windows are shown including the respective information.

Below, two resulting route map examples are shown that are each based on different specifications.

In Figure 7.3, both the fast route and the social route are calculated and visualized using the *traffic load* as the environmental phenomenon that impacts favorability of route options. As the route visualization style, the visual variable *distortion* is chosen and traffic load is visualized on the road network. The recommended, social route is longer than the fast route, while the symbolization using line distortion aims to advice against choosing the fast route. In this example, the detail information for a random position along the route is shown for the social route.

In Figure 7.4, *air quality* has been selected as the phenomenon that impacts route favorability. In this example, cloud icons of varying size are used as the route visualization style and the areal distribution of pollution is visualized as a background layer. It is important to note that the icon choice differs from those that were previously tested in user studies. The reason for this is that, while icons in general have been found effective for influencing route choice, the earlier tested variant with skull icons was rated relatively low in suitability and attractiveness. Therefore, a less emotive icon that still attempts to symbolize emissions is used. Furthermore, detail information for the fast route is displayed.

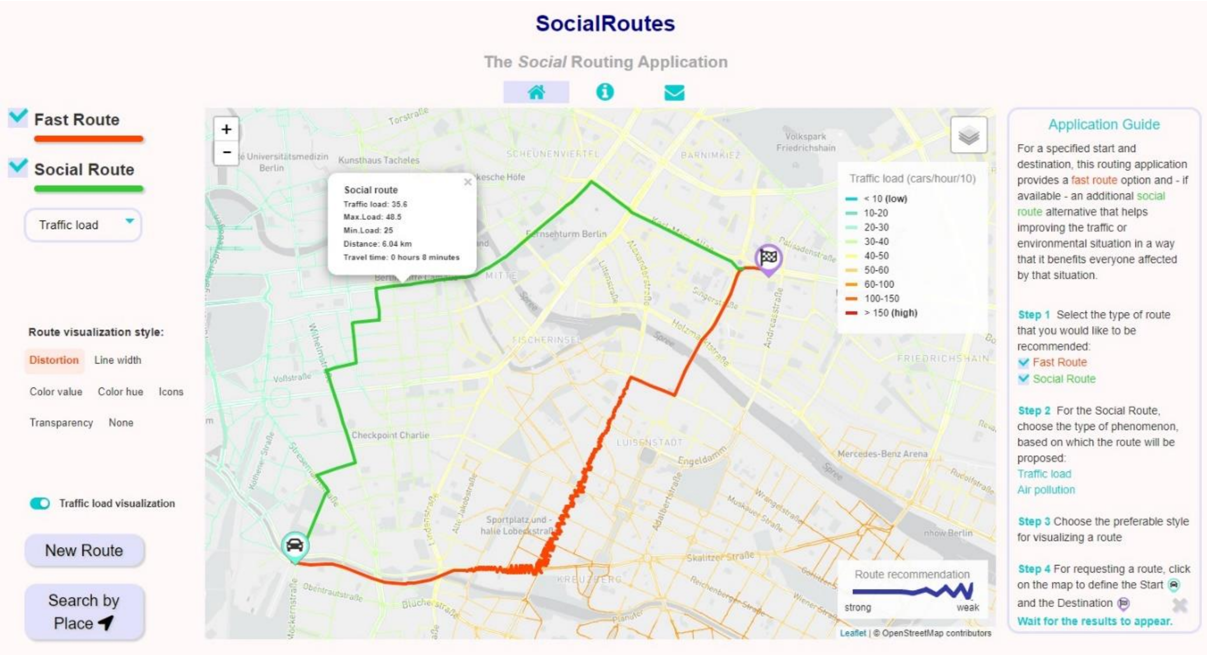


Figure 7.3: Example of a route map result for the traffic load scenario, visualizing a fast and a social route using distortion as a visual variable.

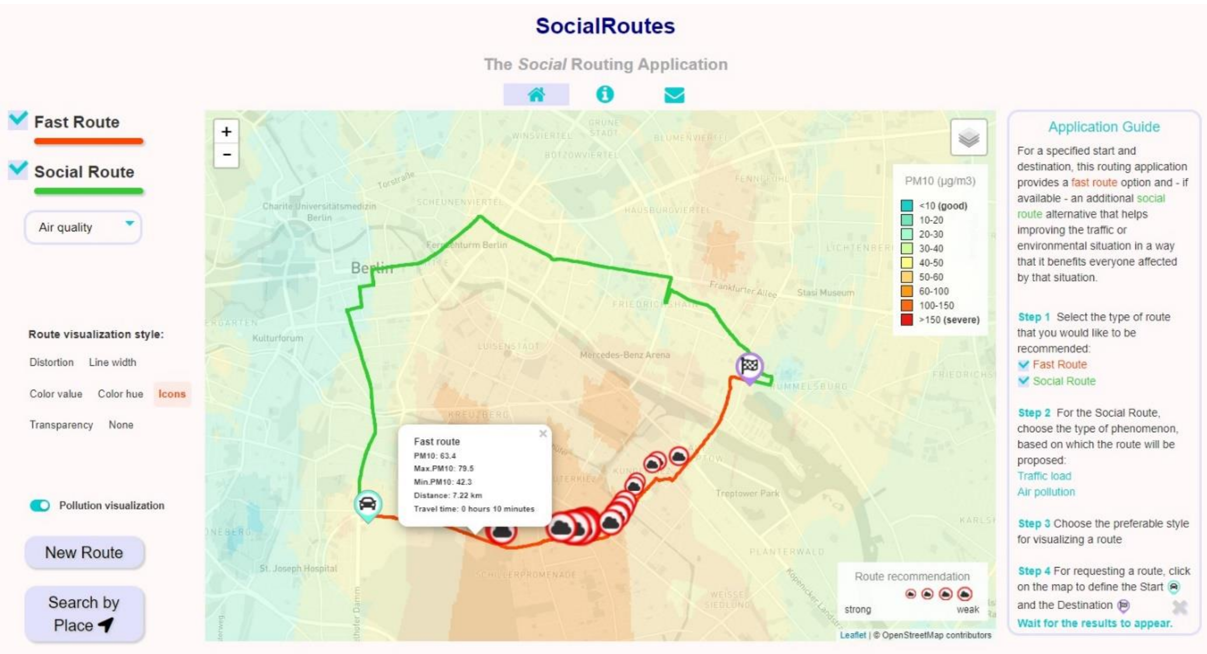


Figure 7.4: Example of a route map result for the air quality scenario, visualizing a fast and a social route using icons as a visual variable.

7.3 User assessment to usability of the application

As part of a usability test, the usability of the developed prototype of the routing application has been assessed by potential users. Unlike the previously described user studies that were focusing on investigating the effectiveness of the design choices made for symbolizing favorability in route maps, the main objective of this test is to assess how the previously introduced methodology is evaluated in a realistic environment, where users can directly experience how the proposed visualizations could work in a real routing application.

Test participants were introduced to the user interface of the application prototype, while the interaction with the different functionalities has been guided by a set of instructions. Afterwards, participants were asked to answer several questions related to the usability of the application.

In short, the instructions included the following information. Note that the same procedure is followed for both types of phenomena (traffic load and air quality):

1. Read the application guide.
2. Select a phenomenon (predefined in the instructions) and a route visualization style of choice.
3. Request a route from any location to any other location on the map.
4. Switch between route visualization styles and moving the start and/or end point of the route to a different location.
5. (Depending on the phenomenon) activate the “traffic load visualization” or the “pollution visualization” layer.
6. Request a new route.
7. View the results and hover the cursor over the route for additional information.
8. Choose a visualization style and calculate a new route between a specified start and end location, by using the “search by place” function

Providing instructions intends to make sure that participants would interact with all relevant functionalities of the application and therefore to control that all participants have a similar amount of experience in interacting with the application. However, participants were also allowed to further explore the user interface on their own to get familiar with the functionalities.

Based on their interaction with the application, for both types of phenomena, participants were first asked to rate how likely they are to choose the *social route* that is recommended. In both cases, the start and end locations within Berlin share some common characteristics. For ensuring comparability for the purpose of the usability test, for both types of phenomena, the distance between the start and destination location is similar, and since in both cases the fast route traverses roads with a low recommendation, the proposed detour for the social route is similar in distance. The choice is made based on the visualization style selected by the participant. Likelihood is assessed by using a 4-point Likert scale (without a neutral option), to ensure that participants decide on a particular point of view. Further questions relate to an estimation regarding the preferred route visualization style for recommending routes (may differ from the style selected for the purpose of route choice), and the usefulness of the traffic load or pollution visualization layer when deciding for a route option.

This first part is followed by a second part focusing on general questions concerning the usability of the application. These questions relate to estimating the satisfaction with general usability, the visual representation of results and the performance of the application. Concerning general usability, the question specifically relates to how easy it was to interact with the functionalities, while concerning performance, the focus is on assessing, if the visualization results were provided reliably and fast enough. Furthermore, it is asked how intuitive the user finds the user interface, how likely they are to use an application that provides this type of information, and how interesting they find the idea behind the application. All previously mentioned questions are answered on a 5-point Likert scale. Importantly, according to the Likert scale bias matrix, it was decided to always show the negative statements on the left side of the horizontal scale, while showing the positive statements on the right side. The bias matrix suggests that for a horizontal Likert scale, bias level is reduced in case negative statements are placed on the left side, since in general participants of online surveys tend to choose an answer placed on the left side of a scale and prefer to choose a positive statement.

Furthermore, two additional questions ask for providing feedback in free text format. The first question asks for describing any problems that may have occurred when interacting with the application, while the second question asks for additional suggestions regarding customizations, features or visualizations.

The usability test took place in a lab environment under supervision of the experimenter. The experimenter observed the interaction behavior of the participants and offered assistance in case they had questions related to the functionalities of the application, or in case of technical issues. Participants were tested one-by-one, each following the same procedure: After the participants were informed about the objectives of the usability test and the sequence of tasks to be fulfilled, they were introduced to the user interface of the routing application, which was running locally on a laptop. In parallel, participants were provided with the above explained set of instructions for helping them getting familiar with the functionalities. Based on their experience with the application, they were then instructed to answer the above explained set of questions.

7.4 Usability test – Results

The usability of the routing application has been assessed by eight test participants. The usability test was intended as an initial evaluation of the application that aimed to assess usability on a highly subjective and individual level. Hence, the test was not intended to yield statistically significant results across a larger user group, so that the comparatively small sample size was considered sufficient for this purpose. Results related to the route choice task that is based on two pre-specified locations, show that for both types of phenomena, most of the participants would follow the recommendation for choosing the social route (see Figure 7.5). While for the *traffic* scenario all participants chose either the *very likely* or *rather likely* option, for the *air quality* scenario 75 % choose the social route and some participants were *rather unlikely* to choose the social route. This result is similar to the observation made in the previously presented user study (see chapter 6.3.6.1) in which participants were more likely to *definitely* choose the *societally favorable* route in the *traffic* scenario.

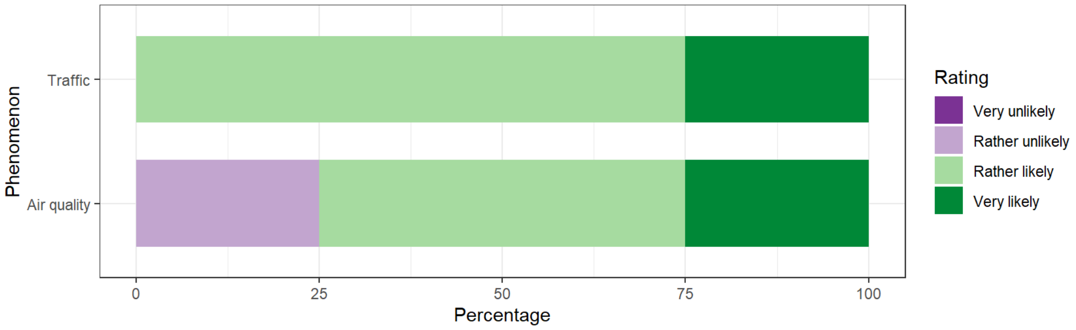


Figure 7.5: Likelihood of choosing the social route.

Tables 7.1.A and B show the likelihood of choosing the social route depending on the route style that the participant has selected. In case of air quality, it can for example be seen that when participants chose the route style *icons*, they were more likely to choose the social route than if they chose the route style *color hue*.

Table 7.1: Likeliness of choosing the social route (in percent of participants) depending on the selected route style for the phenomenon A) traffic and B) air quality.

A) Traffic

	Selected route style				
	Color hue	Color value	Distortion	Icons	Line width
Rather likely	25	0	0	37.5	12.5
Very likely	0	12.5	12.5	0	0

B) Air quality

	Selected route style			
	Color hue	Distortion	Icons	Line width
Rather unlikely	25	0	0	0
Rather likely	25	12.5	0	12.5
Very likely	0	0	25	0

Results concerning the preferred style that should be used for visualization in a routing application (see Figure 7.6) reveal that, for the *traffic* scenario, the three route visualization styles *color hue*, *distortion* and *icons* are preferred over the other options *line width*, *transparency* or using no graphical variations in symbolization. Interestingly, rather unconventional styles such as *distortion* and *icons* seem more preferred than the commonly known style using variations in color hue. A similar pattern can be observed for the *air quality* scenario, while here color hue and icons are preferred by the majority of participants.

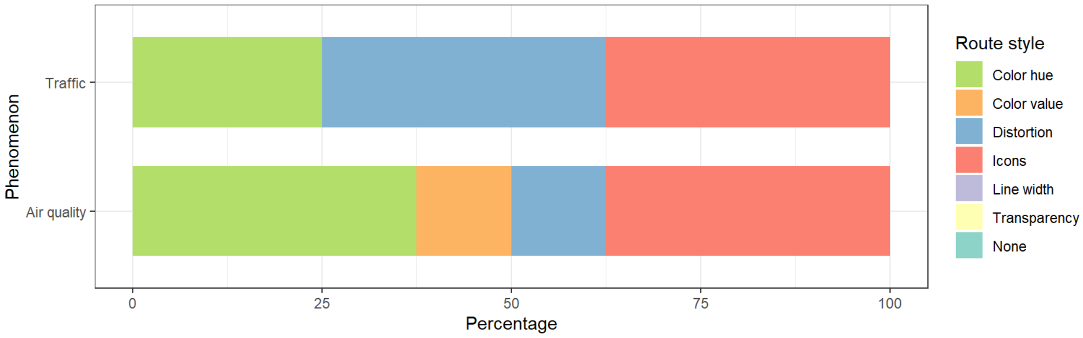


Figure 7.6: Preferred route style for visualization in a routing application.

In addition to visualizing the route options themselves, in case of the *air quality* scenario, participants clearly assess showing an additional layer with information on areal distribution of air pollution as useful (see Figure 7.7). For the *traffic* scenario, however, participants seem less convinced that showing an additional roads layer with traffic load information is useful. According to a comment of one of the participants, the background layer visualization might be less useful for car drivers in terms of traffic, since they might want to focus on the situation along the suggested route itself. Furthermore, several participants mentioned that the additional layer helps them to estimate, if there are additional route options (other than the proposed ones) that possibly make sense.

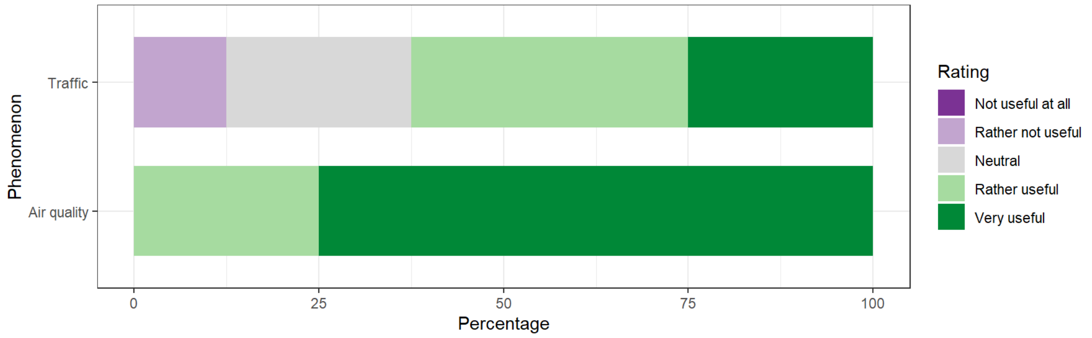


Figure 7.7: Usefulness of visualizing an additional layer with environmental information.

Figure 7.8 visualizes the results related to questions including a rating that asks for satisfaction with usability, representation and performance. It is clearly visible that participants were mostly satisfied with the usability of the application and visual representation. Regarding performance, however, the majority of participants was not very satisfied. As participants have reported, the main reason for this is that loading times for the route visualization were relatively long. Since the application was running on a local server, this may be due to a relatively low processing power of the used computer.

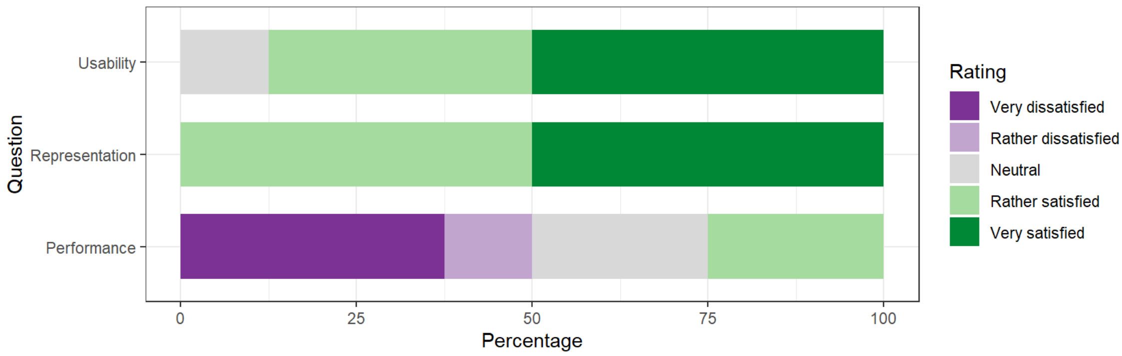


Figure 7.8: Users' satisfaction with usability, visual representation and performance of the application.

Responses to questions concerning the intuitiveness of the user interface, the likelihood of using the application and the interestingness of the idea behind the application are predominantly quite positive (see Table 7.2). The vast majority agrees to the user interface being very intuitive and the application idea being very interesting. In terms of using the application, 25 % of the participants were undecided, if they might want to use an application that provides this type of information, while all other participants reported that they are likely to use the application.

Table 7.2: Users' estimation regarding intuitiveness of the user interface, likelihood of using the application and the interestingness of the idea behind the application.

User interface		**Using the application**		**Application idea**	
Rating	%	Rating	%	Rating	%
Very unintuitive	0	Very unlikely	0	Very uninteresting	0
Rather unintuitive	0	Rather unlikely	0	Rather uninteresting	0
Neutral	0	Neutral	25	Neutral	0
Rather intuitive	12.5	Rather likely	12.5	Rather interesting	25
Very intuitive	87.5	Very likely	62.5	Very interesting	75

Responses regarding problems encountered when interacting with the application primarily relate to the earlier described loading times of the route visualization. Suggestions for possible customizations of the application and proposals for additional features, however, are quite diverse. Regarding a possible improvement of the design of the user interface, test participants propose to make the route visualizations more intuitive by adding labels for the fast and social route next to the route visualization or providing navigation information such as distance or duration directly attached to the route visualization, rather than showing it in a popup window. A similar idea relates to automatically showing the number of cars that are on the road and to add textual information on travel time differences between the route options. Furthermore, including additional road-related information such as traffic lights or additional layers with information about traffic accidents or similar traffic safety aspects in the visualization is desired by some participants. Regarding the route visualizations themselves, participants propose to make differences in symbolization more clearly visible, even if the differences are in reality not very large. Otherwise, it might be not so clear why the social route should be chosen. This suggestion corresponds to the different levels of intensities of symbolization, tested in user study 2 (chapter 6.2). Since it has been found that a clear visual distinction between the favorable and non-favorable route was effective for influencing route choice, it might be beneficial to adapt the route map representations produced in the application by intensifying the graphical differences in symbolization. Another idea was related to also introducing "positive" icons for route parts with a high level of recommendation. Some participants further would like to see an option to show more than two possible route options.

Regarding other elements of the user interface, participants suggest to make the search bar for the directions more prominent by placing it above the map, and making the functionality more easily recognizable by using a magnifier symbol. Additionally, a permanently visible *get route* button could support the understanding of the user that a route is requested. Furthermore, some participants would like to see more options for base map styles, for example one that includes information on points of interest or an aerial photograph. However, colorful base maps might lead to visibility issues, in particular when the route visualization uses variations in color.

In general, several participants propose to customize the application for bicycle routing, since particularly air quality might have a larger impact on cyclists in terms of route choice. Also, some participants wish to make the application usable for further areas and cities, which could be addressed in an updated version of the application.

It is important to note that the proposed customizations, as well as the results of the questionnaire are based on a small sample size. This means that the results cannot be assumed to be generalizable for a large group of users. However, most of the results show clear patterns among the tested participants and therefore provide valuable feedback for estimating the usability of the application. Accordingly, the results of the usability test indicate that the topic addressed with this application is of great relevance for the majority of potential users. Given that the performance of the application would be improved to meet the users' expectations, most participants are satisfied with the design of the application and would use such an application in order to contribute to improving environmental issues related to road traffic.

To provide a qualitative estimation regarding the user responses concerning usability of the application, Figure 7.9 shows a graphical summary for different tested aspects.

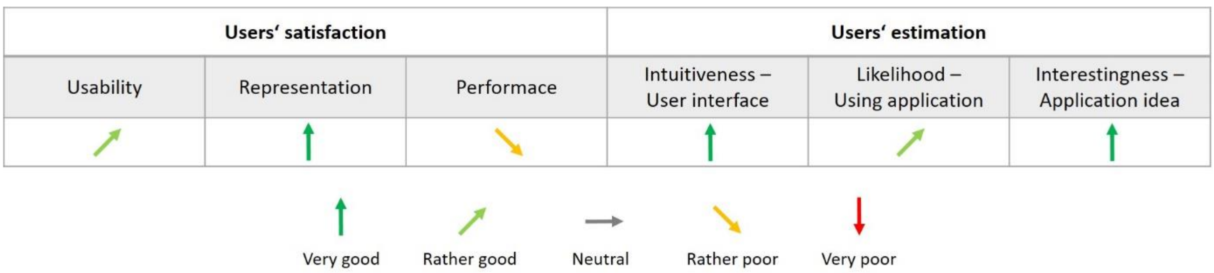


Figure 7.9: Qualitative evaluation of the user responses concerning usability of the application in different aspects.

7.5 Limitations and future adaptions

As described, the presented routing application has been developed as a prototype version including some limitations. First of all, the geographical area of application has been delimited to the city area of Berlin, due to limited availability of suitable data – particularly concerning air quality measurements. Furthermore, the application is currently not providing real time route recommendations. Rather, the recommendation is based on preprocessed data on a specific time stamp retrieved from a database in .csv format. Therefore, one of the main objectives for improving the usability and effectiveness of the application is to extend the geographical area of application. Area-wide application in both urban and rural areas depends heavily on data availability on the environmental phenomena being measured, so additional data sources may need to be incorporated. Additionally, an updated version of the routing application intends to provide route recommendations based on real-time data of the measured phenomenon. This would be a necessary requirement for providing meaningful information on *social* route options, for which the recommendation may change dynamically based on changes in the data that describes the phenomenon. Further adaptions could involve adding textual information on actual travel time, or travel time differences between the route options.

Moreover, since routing applications are usually not only used for planning a trip, but also when actually traveling, the development of a mobile version of the application is suggested to be useful when implementing the approach on a large scale. Provided that real-time data is available, the application is proposed to be extended by a navigation component. That is, based on a temporary change in the traffic- or environmental conditions, the route recommendation will be adapted dynamically, while potentially leading to different route sections being recommended and visualized as part of the social route option at the next point in time. Additionally, navigation instructions could be added to enhance user-friendliness of the application.

Finally, once all previously proposed adaptions are implemented, the application is intended to be running on a public server, instead of the current solution of using a local server. The public server solution is expected to also improve efficiency and performance of the routing application.

8 Implications of the findings

While in chapter 6, the results of the user studies that have been performed as part of this thesis were discussed individually, in this chapter, the relevance of the findings from the different user studies is compared and further discussed in the light of potential future developments in cartographic design.

The chapter starts with an assessment regarding the agreement with the key hypotheses developed in chapter 1.2, followed by an assessment regarding *successful* design variants for influencing route choice towards a *societally favorable* route. Based on this discussion of the main findings, in a further section, some limitations and challenges related to the methodology applied in this thesis are discussed, including the acceptance of unfamiliar visualization types. The chapter concludes with a section on suggestions for future research directions and the contribution of the dissertation.

8.1 Agreement with key hypotheses

This sub-chapter provides an overall discussion of the findings gained from this thesis, with a focus on their agreement with the key hypotheses developed earlier in chapter 1.2.

Overall, the results presented in this thesis have shown that the proposed methodology for visually communicating *societally favorable* routes has been found effective for evoking a behavior change in travelers. In the following, the level of agreement with each of the three key hypotheses will be discussed in more detail.

Hypothesis 1: Visual communication using cartographic symbolization is effective for influencing a traveler's route choice towards a longer, but *societally favorable* route (verified in *Fuest et al., 2021* and *Fuest et al., 2023b*).

In general, the findings of this work verify that using cartographic symbolization for visually communicating favorability in route maps is effective for influencing a map-reader's route choice towards choosing a longer, but *societally favorable* route. Evidence for this has been found both in *user study 2* (Fuest et al., 2021; chapter 6.2) and *user study 3* (Fuest et al., 2023b; chapter 6.3). While *user study 2* tested the effectiveness of visual modifications of line objects in the *traffic* scenario, *user study 3* compared effectiveness for both line and area objects, as well as variants using combinations of both geometries, in the two scenarios *traffic* and *air quality*.

User study 2 has shown that the tested six different design variants have a significantly different influence on route choice behavior. In particular, results have shown that the willingness to choose the *societally favorable* route seems to increase with the level of intensity of the modification. This finding confirms that symbolization as such seems to be an important factor when making a route choice decision. The results of this study have further shown that visual characteristics of visual variables need to be selected carefully, so that people understand the visual metaphor that is communicated and consequently are more likely to follow the route recommendation.

Findings from *user study 3* further confirm effectiveness of cartographic symbolization for nudging travelers to *societally favorable* routes for all tested 14 design variants. Although all visualizations were found effective, the user study has found differences in effectiveness between the different design variants and the scenario that is communicated. In particular, results suggest that participants' willingness to follow the route recommendation strongly depends on the visualization that has been chosen for communicating a specific scenario.

The usefulness of different design variants tested in the various user studies for symbolizing route favorability in different scenarios is discussed in more detail in the following chapter 8.2.

Hypothesis 2: Application of cartographic symbolization methods to route map visualizations can be generalized across different environmental phenomena, while the effectiveness of different types of symbolization for influencing route choice and their suitability for communicating the respective phenomenon vary among different scenarios (verified in *Fuest et al., 2023a* and *Fuest et al., 2023b*).

The methodology introduced in chapter 4 and 5 of this thesis proposes a routing- and subsequent route map visualization procedure that is not limited to one specific scenario, but can be applied to various scenarios, as long as observed values of a phenomenon and a critical threshold for determining levels of favorability, are known.

The applicability of different design variants of route visualizations to different scenarios has further been tested as part of *user study 3*. As hypothesized, the results of the user study have shown that the most appropriate design decision for nudging a traveler's route choice towards a *societally favorable* route varies depending on the phenomenon that is communicated. In particular, results have shown that line type visualizations were most effective for the *traffic* scenario (e.g. colored line), while in the *air quality* scenario, area symbols were more effective (e.g. colored background). This indicates that an effective map symbol needs to correspond to the geographic extent of the real-world phenomenon.

Similarly, the evaluation of results regarding suitability of different design variants confirmed the appropriateness of line-type visualizations for the road-focused *traffic* scenario, and area-type visualizations for the environment-focused *air quality* scenario. This pattern is assumed to be transferable to further scenarios.

The findings of this thesis have shown that a generalization of the proposed visualization concepts for application to various scenarios is only effective, if the used map symbol is found appropriate for communicating the corresponding scenarios.

Hypothesis 3: Emotional responses to map symbols contribute to a traveler's route choice decision making (verified in *Fuest et al., 2023b*).

The influence of emotional responses to map symbols on route choice decision making was investigated in *user study 3*. Results of the study have shown that routes communicated as favorable primarily evoke positive emotions, while routes communicated as non-favorable primarily evoke negative emotions.

Particularly in the *air quality* scenario, negative emotions have generally been evoked more frequently than in the *traffic* scenario. This suggests that negative consequences related to this type of environmental phenomenon seem to play a more important role in decision making than for the *traffic* scenario. Furthermore, it has been found that negative emotions towards the societally non-favorable route are more likely to affect route choice behavior than positive emotions towards the favorable route. This pattern was observed to a greater degree in the *air quality* scenario. Considering the higher level of negative emotions felt for the maps depicting *air quality*, negative emotions associated with environmental issues such as air pollution indeed seem to have evoked a behavior change towards a more *societally favorable* route choice decision.

In general, the findings of this thesis have shown that different types of symbolization evoke different emotions that in some cases seem to contribute to decision making. The findings therefore demonstrate the importance of appealing to people's emotions in the context of the communicated situation for evoking a behavior change in route choice (Roeser, 2012), which is suggested to be achievable by applying suitable map symbolization.

8.2 Assessment regarding *successful* design variants for influencing route choice towards a *societally favorable* route

The following section provides an estimation regarding which design variants turned out being overall successful for visualizing the phenomenon that is intended to be communicated to the map-reader. The estimation is based on the results of the previously described user studies, while *success* is evaluated based on the measured factors *effectiveness*, *suitability*, *intuitiveness* and *attractiveness.*

The results of the different user studies have shown that there is no single design variant that is ideal in terms of effectiveness for influencing route choice and suitability for visually communicating the relevant information. Moreover, it was found that the most effective use of symbolization differs depending on the scenario. It is important to note that for the design variants that were tested in more than one user study, the corresponding terms from *user study 3* are used, while for all other design variants, the terms used in the descriptions of the respective user study are used.

For the *traffic* scenario, the *Color Line* (*CLn*) variant, which is widely used for visualizing traffic information, was successful based on several factors such as effectiveness, suitability, and helpfulness for decision making. Due to their familiarity with this type of representation, map users may have felt comfortable making decisions based on the symbolization. However, results from *user study 2* also indicate that the use of an unfamiliar color scale can reduce effectiveness and lead to unusual findings.

Another variant that is suggested to be successful for communicating traffic information is the variant *Icons Line* (*IcL*), which uses symbols for communicating *societally favorable* and *non-favorable* parts of the route. Like the *CLn* variant, the *IcL* variant evoked positive emotions for the favorable route among a particularly high percentage of participants, which indicates that the symbolization successfully communicated the sentiment that should be associated with the route. Since the performance of the selected sign was not compared with other possible options, its effectiveness might be altered (either positively or negatively) by choosing a different sign. For example, the *symbols* variant tested in *user study 2* used car icons for communicating traffic levels. Similar as for the *IcL* variant, the used symbols were found effective for visually communicating *societally favorable* routes. Another example in this context is the *IcA* variant that uses skull icons for symbolizing pollution levels. While this variant was found effective for influencing route choice, it was estimated as less suitable or attractive for symbolizing the corresponding information. This indicates that signs are generally appropriate visual means for influencing the map-reader's route choice – however, the symbol choice needs to be considered carefully. For example, a further design variant using cloud symbols, which has been tested as part of the web-based routing application described in chapter 7 for symbolizing air pollution, yielded promising results regarding both effectiveness and user preference.

Although the *Color Line* (*CLn*) variant also performed reasonably well for the *air quality* scenario in terms of effectiveness, suitability, and helpfulness, here, a different type of visualization is proposed as successful. The variants using a color area background (*CAr*, *CSp*, *CSz* and *CDs*) were clearly effective for communicating air quality. This effectiveness seems to have been influenced by the emotions evoked by the map representations. For the variants *Color Spikes* (*CSp*) and *Color Distortion* (*CDs*), there was a significant relationship between a negative emotion related to the non-favorable route and a route choice decision in favor of the *favorable* route. Hence, map users seem to have successfully interpreted the symbols as an environmental hazard that should be avoided. However, results show remarkable differences between these four variants concerning their effectiveness and rated suitability. While the *Color Area* (*CAr*) variant seems less effective on its own for influencing route choice, it was rated as the most suitable among the four color-area-based variants for visually communicating air quality information. Its effectiveness for influencing route choice, however, increased when an additional visual variable was added to the color area representation – with the *CDs* variant featuring the largest improvement. This improvement may have been due to the particularly high percentage of negative emotions felt for the non-favorable route. Considering its high effectiveness for influencing route choice, the *CDs* variant is proposed to be successful for nudging travelers to a *favorable* route that would help to improve air quality. However, since other color area-based representations have also been found effective, further combinations with other visual variables are likely to turn out to be successful, too.

8.3 Limitations and challenges

Although the methodology developed for symbolizing favorability in route maps, as well as the methodology for testing usability of the proposed design variants has been prepared carefully, the approaches described as part of this thesis come with a few limitations. The following section presents a selection of potential issues related to the methodology applied in this thesis.

Since the proposed approach for calculating a *societally favorable* route leads to recommending longer routes that avoid areas with high levels of air pollution, a possible increase in pollution levels cannot be prevented for previously less affected areas due to emissions. However, the effect of the proposed method is to achieve a more even distribution of traffic (Graphmasters, 2020), as the recommendations dynamically would be adapted to the critical values. Furthermore, spatial clustering of extremely high particulate matter levels is avoided, which contributes to reduce critical pollution levels that are particularly hazardous to health. As the recommended routes are typically longer than the shortest connections, there is, however, an increase of the amount of emissions. With the current calculation method, the resulting increase in route length for the recommended route directly depends on the spatial distribution of emissions. In this regard, optimization of the method is planned in terms of defining and implementing a suitable route length to potential health risk ratio as an additional factor. This ratio intends to provide information on the reasonableness of making a detour of a specific length given a specific pollution level.

Furthermore, since very large detours are not considered as *societally favorable*, a maximum detour length could be defined. In the user studies described in this thesis, detours were intentionally kept relatively short, since in addition to social implications, individual efficiency is expected to decrease with larger detours. Hence, travelers would possibly be less willing to follow the route recommendation, despite the use of map symbolization.

In general, the proposed methodology of visually communicating two route options (fast route and *societally favorable* route), was developed for the use case of inner city routing tasks, since urban road networks usually provides the possibility of alternative route options that allow avoiding critical areas. An adaption of the methodology to rural areas or inter-city routes might be possible, but could lead to larger detours, due to less dense road networks. Hence, reasonable application might be limited to urban areas.

Regarding the use of visual variables for creating the different design variants, a remaining challenge is to make the graphical differences for the various types of symbolization comparable among different design variants. Although the introduced normalization of the value ranges of the different input data ensures comparability, some of the graphical characteristics such as maximum width of a line or maximum number of symbols to be used have been proposed based on a subjective estimation that seemed suitable for the corresponding map representation. For allowing an automated use of the methodology in different applications, a standardization of the visual characteristics might be useful. However, such a standardization may need to consider that the same visual representation of the symbolization might not work for different map backgrounds or different zoom levels of the map. Therefore, the introduced weighting factors could be useful to optimize visual characteristics of map symbols across different map styles and sizes.

A further potential limitation of this work might be related to how the user studies have been set up. Although they were based on realistic route map representations, similar to maps as commonly produced in online routing services or navigation applications, the surveys were carried out under laboratory conditions, without exposing the participant to the actual situation where the route choice would have to be made. While the presented results confirm that route choice decision making can be influenced by symbolizing favorability of route options, actual route choice behavior in situations that require on-site decision making still might deviate from the described findings.

Acceptance of unfamiliar visualization types

As the results of this thesis have shown, some of the proposed design variants for symbolizing route favorability have been found effective regarding intuitiveness, suitability or their potential for influencing route choice. However, despite their estimated appropriateness for being implemented in route maps, some of the visualizations might seem unusual to map-readers, so that they could have difficulties accepting an unfamiliar symbolization of the mapped phenomenon. Particularly in traffic maps, a widely used symbolization relates to the traffic light metaphor for communicating traffic flow. Since this symbology has been adapted by various widely used mapping or routing services, it might be difficult to accept other, less familiar visualizations for the same phenomenon.

Therefore, when planning to implement alternative, uncommon symbolization methods on a large scale, acceptance of such visualizations should to be tested beforehand. Such a user survey could for example involve collecting user feedback for testing an application using ‘traditional’, commonly known symbolization approaches vs. experimental, alternative symbolization types. Since acceptance of map symbols may slowly evolve over time with increasing familiarization, a long-term study that compares user feedback at different times could provide useful insights. Hence, some of the variants tested in this thesis might turn out being widely accepted after getting familiar with them, while other variants might be rejected by users even after getting used to seeing them frequently.

8.4 Suggestions for future research

The methodology as well as the findings of this thesis have shown that there is potential for multiple further research questions related to the overall research topic. Therefore, this sub-chapter provides a selection of suggestions for future research directions that were not yet addressed in the scope of this thesis.

While this thesis exemplarily focuses on investigating the effectiveness of different design variants for influencing route choice in the context of two specific scenarios – namely *traffic conditions* and *air quality*, the proposed methodology allows the application to further environmental or traffic-related scenarios. These could for example include scenarios such as *road safety* for communicating locations with an increased risk of accidents or *public health*, which is related to the spread of viruses or diseases (potentially more relevant for non-motorized traffic participants).

Based on the findings of this research, it can be suggested how the methodology could be applied to further scenarios. In this section, suggestions are exemplarily provided for the *road safety* scenario. As introduced earlier in chapter 4.2, *road safety* can be considered as a point-like scenario, while the usually point-like sources of risk might be better represented as areas that show the impact of a risk- or accident location. Hence, the methodology is suggested to work similar as for the *air quality* scenario, with an important difference of these risk areas rather comprising discrete regions. For symbolizing favorability of route options or the level of uncertainty of a risk, visual variations can be applied to areal symbols, as well as to the boundaries of the impacted areas. Based on the findings of this thesis, it can be assumed that here, variations in color or the use of figurative symbols such as icons might be an appropriate design choice. Since findings related to the tested areal *air quality* scenario have further indicated that symbolizing both line and areal features is effective for communicating favorability in a route map, in case of the *road safety* scenario, route segments in the affected areas may be symbolized as well, in order to strengthen the nudging effect. It can be assumed that design specifications similar to those that have been found effective for symbolizing combinations of line features and areal features in usability testing (such as a distorted line, see chapter 6.3.6.4), might also work for route visualization in the *road safety* scenario.

As part of this thesis, the different scenarios have been considered separately for the application of the methodology. However, there is also the possibility to apply the proposed methodology to a combination of two or more different scenarios, such as traffic conditions and air quality. The application of the proposed methodology to combined scenarios requires the availability of at least one dataset for each individual scenario.

These datasets provide the *observed values* that are further used during the consecutive route calculation and automatic visualization process. The *threshold* values that are required to determine the level of route favorability may differ depending on the scenario. The previously described calculation of the value *r* is also applicable to combinations of two or more scenarios. In this case, for each road segment, the mean of the individually determined *r* values of the different scenarios is calculated. Consequently, this resulting final *r* value is used as part of the automatic routing and visualization procedure.

In case one of the scenarios is temporarily considered as societally more important than the other scenarios (for example *air quality* is considered as more important than *traffic* and *road safety*), it is also possible to assign different weights to the scenarios (here, larger weight to the *air quality*) and then calculate the final *r* value as a weighted average. Since the results of the user studies that have been conducted as part of this thesis indicate that the effectiveness and suitability of different design variants vary depending on the scenario, *successful* design variants for a combined scenario may differ from those for the corresponding individual scenarios.

A further point to consider is that in this thesis, most of the used symbolization followed the principle of loss framing, since research has found that negatively framed information in general has a stronger impact on decision making than positively framed information (Spence & Pidgeon, 2010). However, since gain framing is suggested to be suitable for communication of the severity of environmental impacts, emphasizing positive effects of choosing a route option by suitable symbolization might also turn out being effective for influencing route choice behavior. Therefore, it is suggested to conduct a follow-up study that compares effectiveness of either using loss framing or gain framing in cartographic symbolization for achieving a behavior change.

The usability testing conducted in this work was focusing on investigating the effectiveness of different types of map symbolization on influencing route choice, while the usability of an application that uses the proposed methodology has so far only been tested on a small scale, using a prototype version of a web application. Hence, future work in this direction should investigate the usability of a fully functional online system, and also address possible differences in effectiveness compared to the user studies conducted as part of this thesis.

Finally, another extension of the work conducted in this thesis could involve the inclusion of text with quantitative information, such as the duration of a traffic jam, or information on how much additional particulate matter is added to the atmosphere for different route options.

Scenario-dependent visual route communication for different modes of transportation

In this thesis, the methodology for visually communicating favorable routes has been introduced specifically for car drivers, since motorized individual transport contributes to a large extent to urban traffic congestion and air pollution. However, the methodology is not limited to car drivers, but can also be adapted to other non-motorized modes of transportation such as cycling or walking.

While traffic-related or environmental issues like traffic congestion, air pollution or road safety typically affect all types of road users, these issues may affect different road users in various ways and with different levels of importance. For example, while the level of air quality along a route may be of great importance to a pedestrian or cyclist due to direct exposure to possible environmental hazards (Jarjour et al., 2013; Banister, 2008), car drivers may be less interested in choosing a route with better air quality because they are seemingly protected from external influences (Evans & Jacobs, 1981). In both cases, however, it is important to communicate route recommendations for different types of road users that on the one hand meet the individual needs of road users concerning route choice, and on the other hand contribute to an improvement of different traffic-related and environmental aspects from a societal point of view.

Nowadays there are various routing services available for different types of road users other than car drivers (Müller & Voisard, 2015). While being useful for route planning as such, they rarely address the specific needs of non-motorized road users. Unlike car drivers, road users like cyclists or pedestrians are much more exposed to environmental impacts, and therefore may wish for route recommendations that reduce health- or safety hazards (Jarjour et al., 2013).

There are many different traffic-related scenarios that can temporarily affect a transport system, while each of them might be of different relevance for different types of road users. Furthermore, the effectiveness and intuitiveness of the symbolization used for communicating route recommendations is expected to vary depending on the communicated scenario. Therefore, a follow-up research project could be to develop a scenario-dependent visual route recommendation system that takes into account the needs of different types of road users. This research project could involve the following research questions:

1) Which traffic-related or environmental scenarios are relevant to specific types of road users?
2) To which extent are the scenarios relevant to route choice decisions made by different types of road users?
3) Which cartographic design variants are suitable for representing the characteristics of different scenarios for different types of road users?
4) When creating map visualizations, which weighting is suitable, in case multiple scenarios are relevant for the route choice decision?

All scenarios that are intended to be addressed in the follow-up research are dynamic and may change rapidly over time, and therefore may temporarily lead to different route recommendations based on the current situation. However, static scenarios like the greenest route or the route with fewest turns are not intended to be considered in this project, since these static parts of the environment and route recommendations are unlikely to change frequently.

The proposed methodology could involve the following three main components:

a) Extend the methodology that has been developed in this thesis and adapt it to various different transport modes and a wide range of temporary scenarios that may affect route choice behavior. For this, it is important to first investigate the importance of different scenarios to different types of road users. This could be derived from literature as well as by conducting a user survey.
b) Adapt the calculation of the route recommendations, as well as the corresponding route visualizations to different scenarios and transport modes. For this, design variants of visualizations can be adapted from already developed sets, as well as developed using the design rules for map symbols presented in chapter 5.1. A suitable weighting of various factors needs to be defined for the case that various scenarios are relevant for a road user's route choice, while the relevance of each scenario possibly varies to a different extent.
c) Explore the use of additional ways for communicating the information such as textual information for communicating travel times.

Currently available routing services largely disregard the challenge of providing suitable route recommendations for non-motorized road users such as cyclists or pedestrians and communicating them in an intuitive way. Therefore, when applying the methodology presented in this thesis to modes of transportation different from car driving, special attention should be paid to conducting research regarding appropriate visual variables for symbolizing characteristics that might be specifically associated with a certain mode of transportation.

In this context, a research work recently conducted by Fuest and collaborators (2023c) investigates the appropriateness of different cartographic design variants of bicycle routes for the visual communication of route characteristics, including type of terrain, terrain roughness, terrain gradient, and travel interruptions. A user survey was conducted to assess the effectiveness, attractiveness, appropriateness, and dispensability of a legend of the various display options for the different route features. The results of the survey indicate that many of the proposed design variants are appropriate for the visual communication of bicycle routes. This particularly applies to color representations as well as representations using symbols. However, with respect to the bicycle route features tested, the most appropriate representation heavily depends on the information being communicated (Fuest et al., 2023c). For example, in case of terrain roughness, visualizations using variations in transparency, saturation or the use of symbols have been found most appropriate, while in case of the type of terrain, variants using color or pattern have been found most appropriate. This study highlights the importance of considering the context and characteristics of the scenario to be communicated, in order to successfully symbolize route information.

8.5 Summary and contribution of the dissertation

This thesis investigated the effectiveness of different types of cartographic symbolization for nudging travelers to routes that are favorable from a societal perspective. The methodology involved the development of an automatic route map visualization procedure, which has been exemplarily applied to the two scenarios *traffic* and *air quality*. This procedure includes a routing component for calculating *societally favorable* routes as a preprocessing step, and a subsequent symbolization component for visualizing favorability of route options using different visual variables applied to map symbols. Favorability of routes is defined by calculating the shortest path that also considers environmental conditions. The proposed automatic route visualization allows defining the graphical differences of each visual variable according to the input data to be visualized. The method supports the visual modification of lines, areas or a combination of both. In addition, modifications can be applied to either continuous or discrete objects or phenomena. The proposed design variants for symbolizing route favorability use a large variety of visual variables, including commonly applied variables such as color, size or pattern, but also more abstract formats using cartographic generalization techniques.

To validate the effectiveness of the developed design variants of route maps, three user studies were conducted that investigate subjective and objective usability. Subjective usability was tested by estimating graphical attractiveness, intuitiveness, and suitability of a visualization for representing the communicated phenomenon. Objective usability was assessed by measuring the effectiveness and efficiency of a map symbol, with a focus on its effectiveness for influencing route choice.

User study 1 validated seven design variants of route maps based on criteria for subjective usability for communicating *air quality* information. The results of this survey indicate that some of the proposed design variants can serve as appropriate design choices for rendering route maps that communicate air quality information. In general, it seems that design variants which use a relatively simple symbology with variations in intensity value of color, are preferred over more complex visualizations that possibly combine several visual variables.

User study 2 addressed the potential of different cartographic design variants (in terms of objective usability) for influencing route choice towards a longer but less congested route (*traffic* scenario). The results showed that for most of the design variants, participants' route choice was significantly influenced towards the recommended route. This indicates that the applied visual modifications indeed contribute to a different route choice behavior. It was also found that for most variants, the willingness to choose the recommended route increases with the intensity of the modification.

In addition to investigating the effectiveness of the proposed design variants for influencing route choice, *user study 3* examined the relationship between route choice and emotions in the two scenarios *traffic* and *air quality*. In particular, it was investigated to which extent map symbols evoke positive and negative emotions and whether these influence route choice decision making. The results of this user study further confirm that map symbols can be used effectively for influencing route choice towards choosing the favorable route for the two tested scenarios. While visualizations that modify only lines were more effective in the *traffic* scenario, area symbol modifications were more effective for the *air quality* scenario. The symbolization evoked a wide range of emotions in participants. While non-favorable routes mainly evoke negative emotions, favorable routes mainly evoked positive emotions or no emotions. The results further demonstrate that for some of the design variants, emotions felt in response to the map visualizations contributed significantly to changing the route choice decisions in favor of the *societally favorable* route option. The impact of emotional responses is particularly noticeable concerning routes that are communicated as unfavorable with respect to air quality, while showing a potentially hazardous situation.

Finally, a prototype of an interactive web map application was developed based on the findings of the user studies. The application intends to provide potential users a platform for computing and visualizing routes according to the developed methods. A usability evaluation of the application has shown that most of the potential users provide positive feedback regarding usability, visual representation or the likelihood of using such an application.

Overall, the results of this thesis demonstrate the effectiveness of using cartographic symbolization for achieving a behavior change in route choice, while an effective use of different visual variables depends on the information to be communicated. In terms of route planning services, there is an emerging trend towards recommending more societally beneficial route alternatives instead of only time efficient routes. Therefore, different than other works in the field of visual communication using cartographic symbolization, the focus of this work is on nudging travelers to change their route choice behavior for achieving a societal benefit.

The findings of this thesis intend to raise awareness of the necessity to visually communicate favorability of route options in order to motivate people to improve traffic from a societal perspective. The findings therefore indicate that future routing services should not only consider providing the shortest or fastest route options, but also take societally beneficial criteria into account. The results presented as part of this thesis further verified the importance of appealing to a person's emotions related to the experienced situation, in order to achieve a behavior change.

Ultimately, this research contributes to a novel, emerging trend of developing more environment-focused routing approaches that contribute to improving road traffic from a societal perspective. The findings of this work therefore aim to support practitioners such as developers of routing applications or navigation systems in their design choices for effectively communicating route recommendations in different traffic-related or environmental scenarios.

Appendix

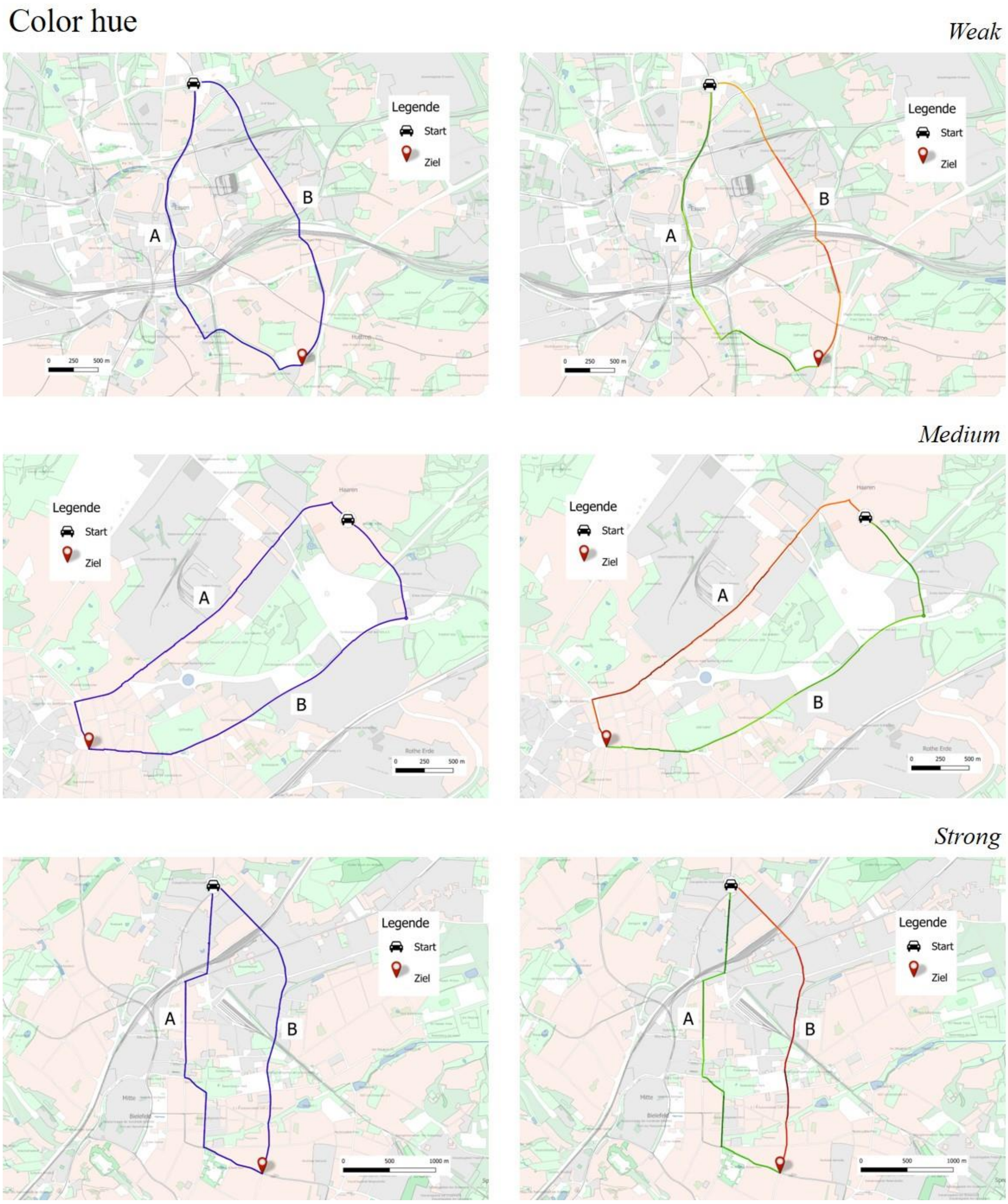


Figure A.1: Route maps prepared for user study 2 using the color hue design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

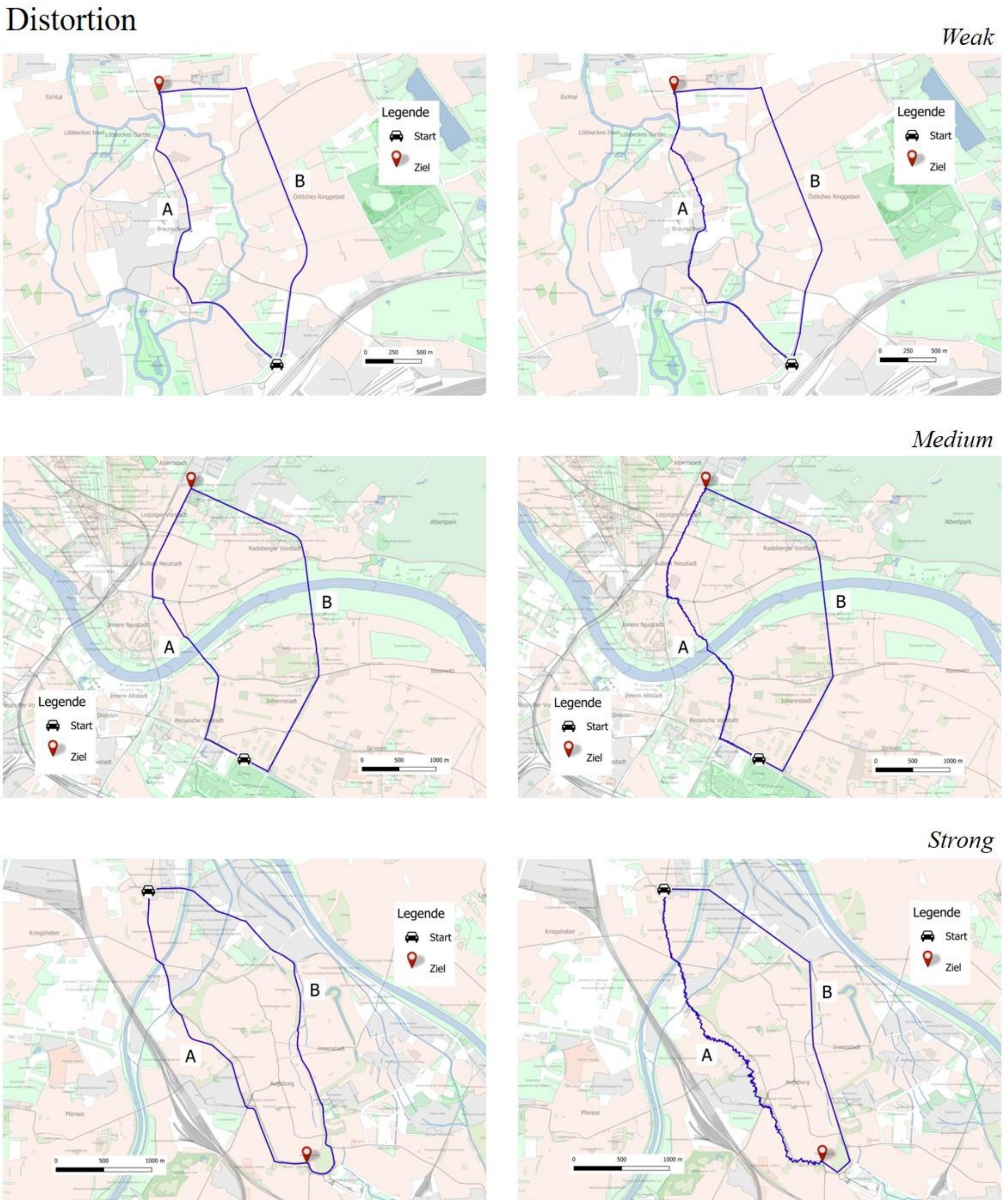


Figure A.2: Route maps prepared for user study 2 using the distortion design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

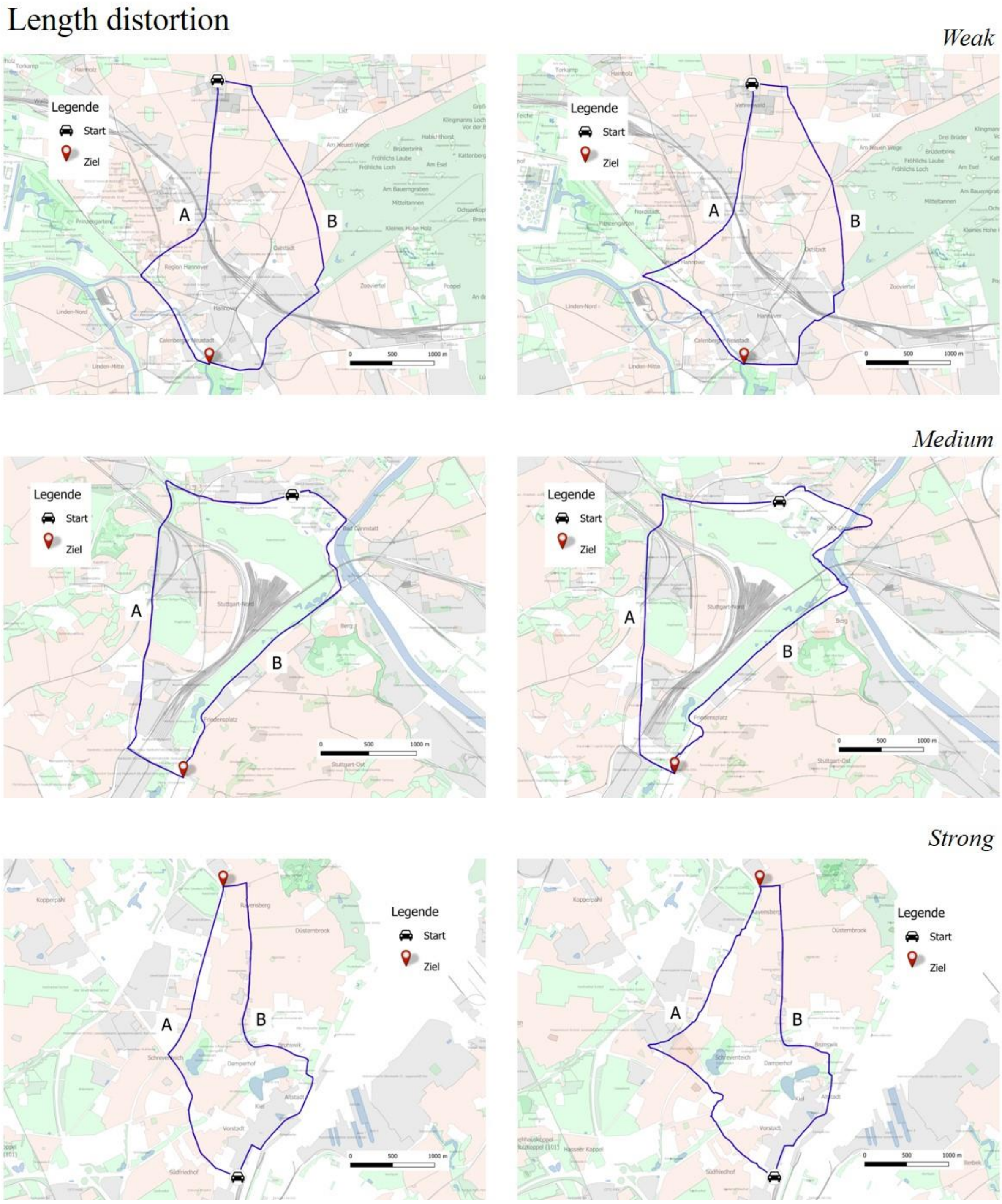


Figure A.3: Route maps prepared for user study 2 using the length distortion design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

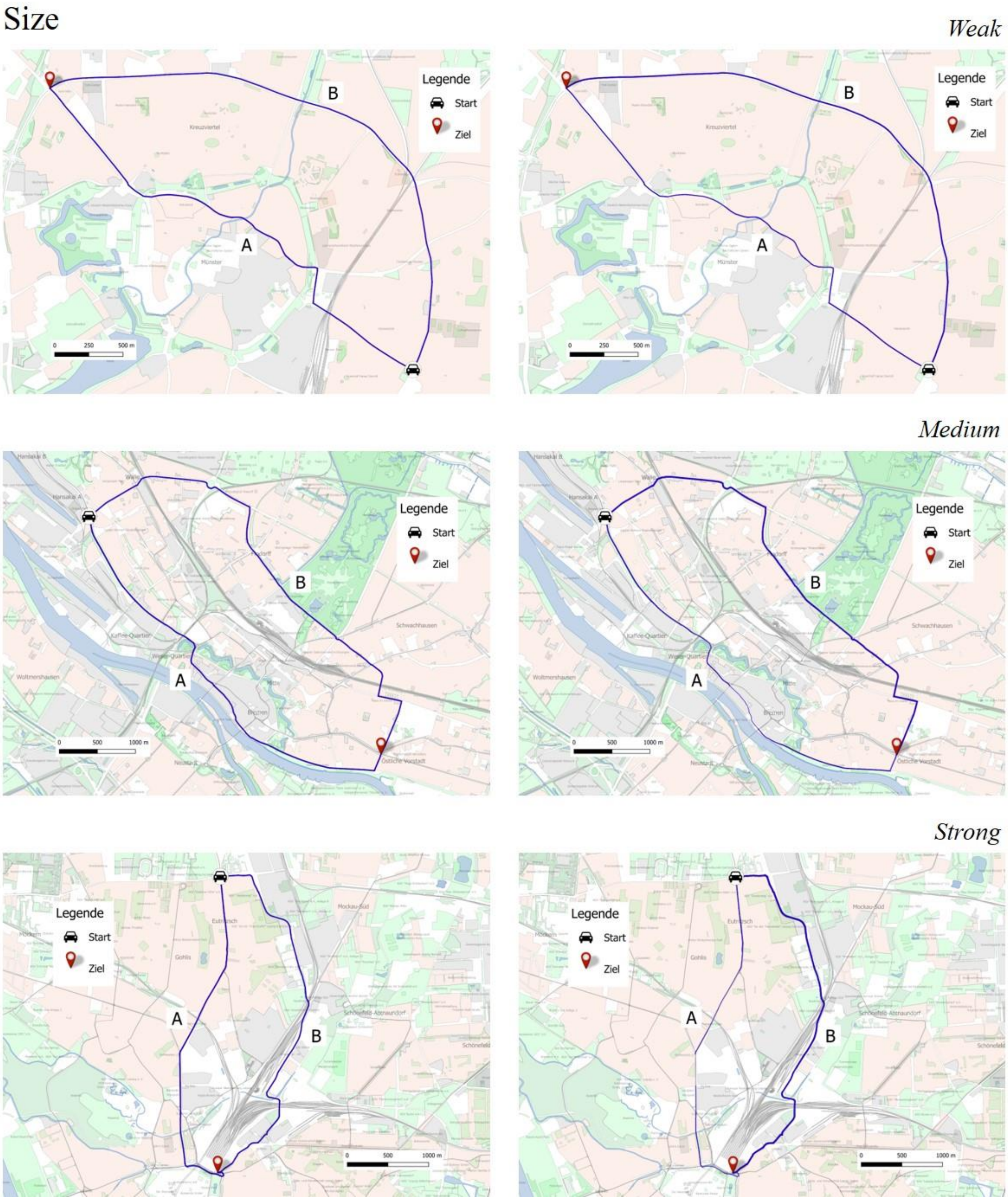


Figure A.4: Route maps prepared for user study 2 using the size design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

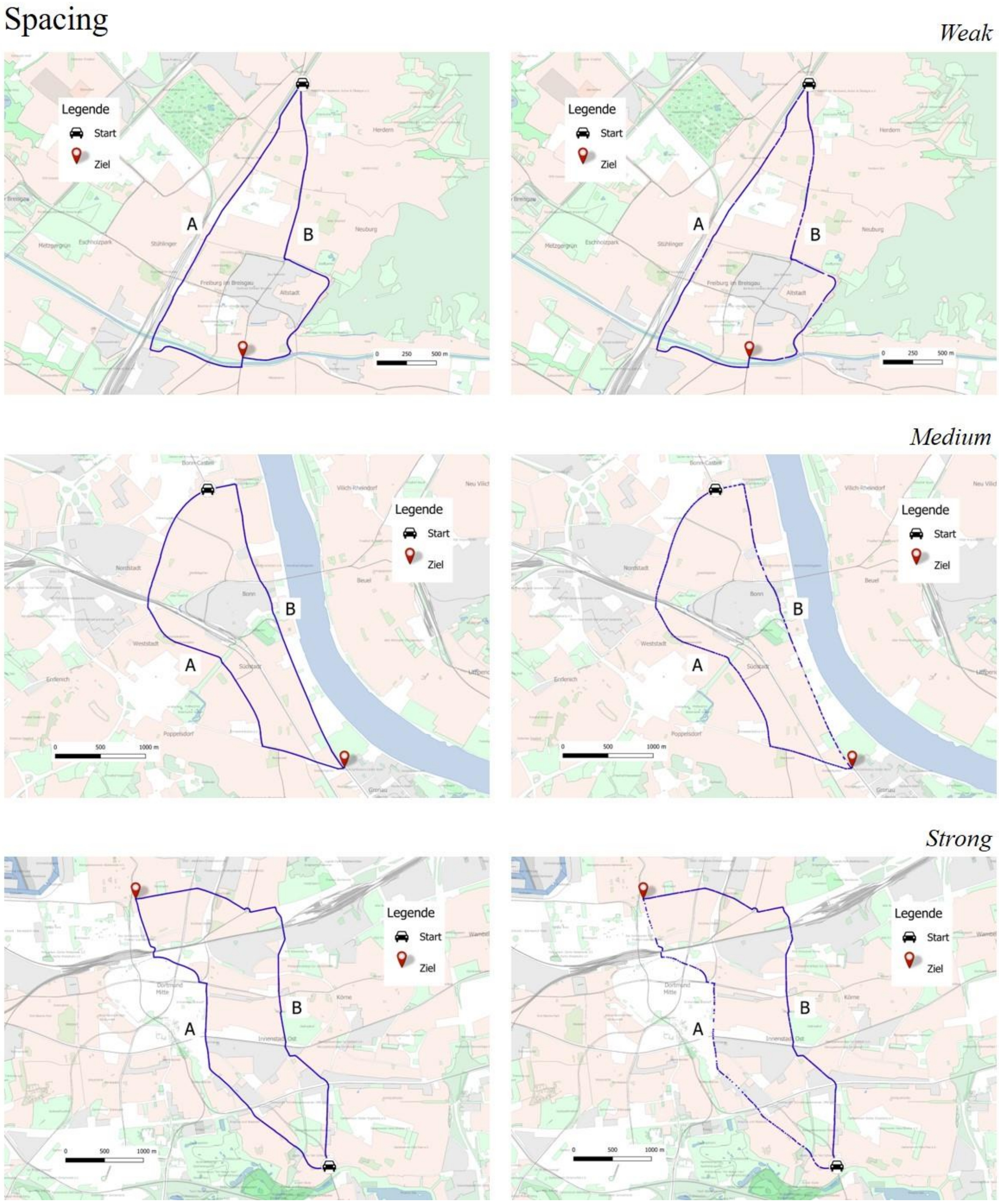


Figure A.5: Route maps prepared for user study 2 using the spacing design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

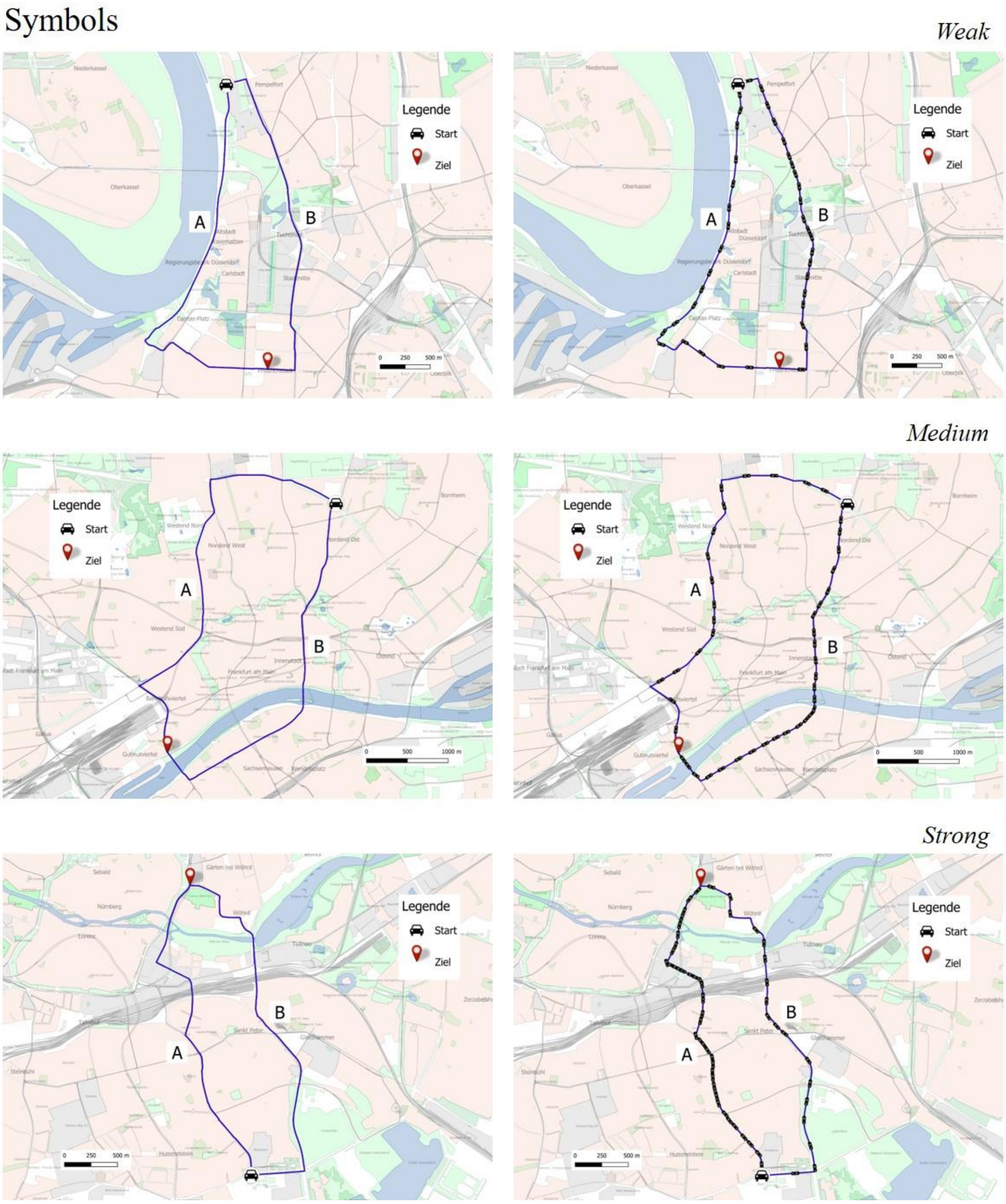


Figure A.6: Route maps prepared for user study 2 using the symbols design variant with the three different levels of intensity. Non-modified maps are shown on the left, modified maps on the right. Map data from OpenStreetMap.

Figure A.7: Non-modified route maps that are used as a baseline for the 14 design variants created for user study 3. The figure corresponds to Figure 6.18 showing the modified versions of the maps. Map data from OpenStreetMap.

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