Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Design

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Effects of different map interfaces on cognitive map development

Master's thesis in Interaction Design
Supervisor: Frode Volden
Co-supervisor: Ole Wattne
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Abstract

Relying on navigation systems during wayfinding processes is potentially problematic. One issue with navigation systems, and especially turn-by-turn navigation, is that they may decrease humans' ability to form cognitive maps; our mental representation of the physical environment we navigate in. Past research indicates that the design of the map interface in a navigation system can affect cognitive map development. This report describes a driving simulator-based experiment where participants were tasked with driving three routes with guidance from three different map interfaces. These three interfaces were then compared with regards to their effects on cognitive map development, driving performance and gaze metrics. The experiment finds that using north-up maps with extra landmark information leads to a moderate increase in cognitive map performance, but that this comes at a cost of an increased amount of mistakes and longer time spent not looking at the road.

Sammendrag

Å være avhengig av navigasjonssystemer i veifinningssituasjoner er potensielt problematisk. Ett problem med navigasjonssystemer, og spesielt de med såkalt *turn-by-turn*-navigasjon, er at de kan senke menneskers evne til å bygge kognitive kart; vår mentale representasjon av det fysiske miljøet vi ferdes i. Tidligere forskning viser at designet på kartvisningen i et navigasjonssystem kan påvirke utviklingen av kognitive kart. Denne rapporten beskriver et kjøresimulator-basert eksperiment hvor deltakerne fikk i oppgave å kjøre tre forskjellige ruter med navigasjonsveiledning fra tre forskjellige typer kartvisninger. Disse tre kartvisningene ble så sammenlignet med tanke på hvilken effekt de hadde på utvikling av kognitive kart, kjøreytelse og blikkdata. Eksperimentet finner at å bruke nordorienterte kart med ekstra informasjon i form av landemerker kan føre til en moderat økning i kognitiv kartutvikling, men at det også fører med seg økt mengde feil og lengre tid der føreren ikke ser på veien.

1.1.1. Table of figures

2. Introduction

Navigation systems are everywhere. Most new cars feature them, and so do virtually every smartphone on the planet. They can give you directions for a car trip across continents, as well as guiding you safely to that new restaurant in your own city. A lot of people rely on navigation systems for virtually any wayfinding situation, and understandably so. Most navigation systems feature some sort of turn-by-turn navigation, a sub-feature which calculates a route for the user and tells them when to make actions such as turning in their navigation process.

But reliance on navigation systems in general, and on turn-by-turn navigation specifically, is problematic. Over-reliance on these aids may decrease the ability to learn the spatial arrangement of the area of travel. In other words, using a navigation system will make it harder to learn a new environment. This is due to the decreased development of cognitive maps which occur when relying on navigation systems (Burnett & Lee, 2005; Jackson, 1998). A cognitive map is the mental representation of a physical environment (Kitchin, 1999); an individual mental model of the world that we live and navigate in. Cognitive maps are very important for skills such as distance and direction estimation (Bell, 2012) as well as spatial problem-solving (Jackson, 1998). In addition, well-developed cognitive maps may lead to better transport efficiency and may also have social and psychological benefits (Oliver & Burnett, 2008). People who are more active in the navigation task, as opposed to passively following turn-by-turn instructions, have been found to demonstrate enhanced landmark recognition, route-learning and general area knowledge (Antrobus et al., 2019).

Several studies have pointed out navigation systems as a tool that can support the development of cognitive maps. In 2005, Burnett & Lee proposed a *Learning-oriented vehicle navigation system,* after finding that drivers navigating using turn-by-turn navigation had a worse memory of the area of travel than those using paper maps. Oliver & Burnett (2008) designed a simple model of such a system and found that users of the novel system displayed better memory of driven routes. A review of the participants' hand-drawn maps suggested that they had developed a more sophisticated cognitive map of the area.

This master’s thesis is to a large extent based on the work of Oliver & Burnett (2008) but aims to improve on certain areas. In their study, PowerPoint slides were used to act as the navigation system, and the sample size was quite low (N=16). In this project I am planning to design a navigation system that supports the development of cognitive maps, while creating an interface that is more in line with what one could expect to find in a modern car. Even though the theories in this project could apply to several different navigational applications, such as mobile apps, this project has been designed with the automobile in mind. It is worth noting that while Oliver & Burnett found effects pointing towards an effect of the new system, the differences between the systems did not reach statistical significance.

This master’s thesis is based on a driving-simulator experiment where participants were tasked with driving three routes with guidance from three different map interfaces. These three interfaces were then compared with regards to their effects on cognitive map development, driving performance and gaze metrics.

The primary research question is defined as follows: *Does the design of the map interface in a navigation system affect cognitive map development?* As this thesis is based on automotive HCI research, it is also important to find out if the map interface designs affects important factors in driving, such as driving performance and how much time is spent looking at the navigation system.

3. Background

3.1. Cognitive maps

3.1.1. Definition & terminology

A cognitive map is often defined as a mental representation of a concept. In fields such as psychology and geography these concepts are spatial, and the term *cognitive map* refers to a mental representation of a physical environment (Colman, 2009; Jackson, 1998; Kitchin, 1999). In other words, the term *cognitive map* refers to a person's mental model of how environments (such as building or a city) is laid out and organized, where objects in that environment are placed, and how they are placed in relation to each other. It is a popular subject within spatial cognition research, which concerns the study of knowledge and beliefs about spatial properties of objects and events in the world (Kitchin, 1999; Montello, 2001). Downs & Stea (1973) defines cognitive mapping as a "process composed of a series of psychological transformations by which an individual acquires, stores, recalls, and decodes information about the relative locations and attributes of the phenomena in his everyday spatial environment".

The term *cognitive map* was coined in 1948, when Edward Tolman at the University of California found that rats have an internal representation of where food is located in a maze, even when the layout of the maze changes (Tolman, 1948). In other fields, e.g. operational research and UX design, the term has been used for mental model representations of any type of process or concept (Gibbons, 2019; Langfield-Smith & Wirth, 1992). However, in this project, the term refers to spatial representation exclusively.

The term cognitive map is not without controversy. Jackson (1998) claims that the term cognitive map is misleading because the term suggests that these mental representations bear some resemblance to cartographic maps. This may or not be the case. As a mental construct, cognitive maps are completely individual in content, shape, and form, and they may or may not draw content and inspiration from cartographic maps. According to Siegel & White (1975) cognitive maps "tend to be fragmented, distorted projectively, and often consist of multiple *mini-spatial-representations*." Despite these terminological issues, the term *cognitive map* is very much in use, because it is relatively compact and is widely understood in the field (Jackson, 1998).

3.1.2. Landmark-route-survey-theory (LRS)

Quesnot & Roche (2015) claims that one of the most influential theories in cognitive mapping is based on the work of Siegel & White and is known as the *landmark-route - survey-theory* (LRS). This theory suggests our cognitive map is divided into three levels: Landmark knowledge, route knowledge and survey knowledge.

Landmark knowledge refers to our spatial knowledge about where objects are located. Landmarks are one of the five primary elements (along with paths, edges, nodes and districts) that humans use in wayfinding processes in urban environments (Lynch, 1960). Any object can act as a landmark for a person, and as a person acquires spatial knowledge about the location of these objects, their landmark knowledge increases.

Route knowledge is the knowledge about the paths that connect these landmarks. The term *path* refers to any possible way to navigate between the landmarks. In other words, a shortcut through a cornfield can act as a path, just as a footpath does.

The final and most complex level is *survey knowledge*. The term implies an awareness of the environment's overall configuration and the potential relationships between its different spatial components. (Quesnot & Roche, 2015). Correctly estimating distances and directions is a skill that is requires survey knowledge (Bell, 2012). Well-developed survey knowledge enables the estimation of routes and distances, even in previously untraveled territory. For instance, if a path is going into a forest, and a person can correctly estimate where that path will go, that is a sign of a high survey knowledge. A person's *sense of direction* may be directly related to their level of survey knowledge (Wen & Ishikawa, 2013).

3.1.3. Cognitive map development

Children's ability to form cognitive maps reaches adult levels during early adolescence (Nazareth et al., 2018), and they continue to develop over our lifespan in a process known as ontogenesis. In addition, they are developed through discrete episodes of experience in a process known as microgenesis (Bell, 2012). People either develop cognitive maps directly through locomotion and/or indirectly through paper maps, navigation systems, and sketches

(Burnett & Lee, 2005). Age is an important factor on the ability to develop cognitive maps, with this ability declining as humans get older (Jackson, 1998).

Individually, humans have very different levels of cognitive map development: Nazareth et al. (2018) classifies cognitive map development into three levels: Imprecise navigators (who form only imprecise ideas of routes), non-integrators (who represent routes more accurately but are imprecise in relating two routes), and integrators (who relate the two routes and, thus, form cognitive maps). Cognitive map development is also linked with interest in geographical activities: In M. R. O'Connor's book *Wayfinding* (2019) a cognitive scientist found that the people in countries with a high interest in the sport of orienteering, have more developed cognitive maps, than people in comparable countries.

3.1.4. Cognitive map assessment

Measuring and assessing cognitive maps is difficult, because they are a product of complex processes whose content and timing cannot easily be known or controlled (Lloyd, 2005). Traditionally, cognitive mapping data collection has been conducted with a mix of unidimensional tests (such as distance tasks, direction tasks and naturalistic tasks.) and bidimensional tasks such as sketch-mapping, completion tasks and recognition tasks (For full overview see Kitchin & Freundschuh (2000). In the present, digital software such as *Virtual Silcton* (*Spatial intelligence and learning center test of navigation* (Northwestern University, n.d.) has been used to assess how accurately individuals can learn the layout of large-scale environments.

Asking test subjects to make sketch maps on paper has been one of the principal ways of assessing cognitive map data. Sketch maps are controversial, as they may confound environmental knowledge with the graphic skills of the drawer; place demand on the subject to produce a two-dimensional view of the world from an aerial perspective; may be hard to interpret and quantify because features not included on the map may reflect either lack of knowledge or deliberate selectivity on the part of the subject. In addition, the size of the paper and the subject's starting point when drawing places constraints on the resultant map (Blades, 1990). Despite these issues, sketch mapping is a very popular way of conducting cognitive map assessment, probably due to the speed and feasibility of administering a sketch mapping session in comparison to other methods.

3.2. Navigation systems and cognitive maps

Many people in developed countries have experience using a navigation system. Almost every new car is delivered with one, and the world's most popular navigation application, Google Maps, has been downloaded over 5 billion times on the android operating system alone. Most of these systems feature some sort of turn-by-turn navigation, where the system, based on certain criteria, dynamically creates a route for the user to follow to his or her destination. Often this is accompanied by guidance for when to perform certain actions, e.g., turning (as the name refers to.)

Several researchers have been critical about an over-reliance on navigation systems in general and on turn-by-turn navigation specifically. Jackson (1998) may have been the first author to raise concern about reliance on navigation systems and claims that it "may prevent the normal development of a mental representation of the area." Burnett & Lee (2005) found that that drivers navigating using turn-by-turn navigation had a worse memory of the area of travel than those using paper maps.

One of the reasons for this decline in cognitive mapping ability may be that using a navigation system while driving creates *inattention blindness;* a failure to see and perceive elements in the environment (Fenech et al., 2010). Schwering et al (2017) states that using turn-by-turn navigation is "incompatible with our naturally employed ways of engaging with spatial information". Turn-by-turn navigation forces us to execute instructions separately, one after another, something which conflicts with the human way of gathering and integrating information during the wayfinding process (Schwering et al., 2017).

3.2.1. The importance of cognitive maps

Cognitive maps are an important part of the wayfinding and navigation process. Cognitive maps are very important for skills such as distance and direction estimation (Bell, 2012), as well as spatial problem-solving (Jackson, 1998). People who are more active in the navigation task, as opposed to passively following turn-by-turn instructions, have been found to demonstrate enhanced landmark recognition, route-learning and general area knowledge. (Antrobus et al., 2019). Well-developed cognitive maps may lead to better transport efficiency and may also have social and psychological benefits.

In addition, a lack of spatial understanding of an area may lead to a dependence on the navigation system (Rizzardo & Colle, 2013). These systems may lack content, malfunction or provide incorrect information, which makes cognitive map development very important if the driver is to resume the task of manually navigating if the system malfunctions (Oliver & Burnett, 2008).

3.2.2. Effects on hippocampus

There are known correlations between developing an accurate mental representation of largescale environments and structural brain changes. (Woollett & Maguire, 2011) followed individuals training to be licensed taxi drivers in London over four years, a task requiring knowledge and spatial awareness of over 25000 streets. In those who qualified, acquisition of an internal spatial representation of London was associated with a selective increase in gray matter volume in their posterior hippocampi (Woollett & Maguire, 2011). O'Connor (2019) paraphrases a study by Javadi et al. (2017) and states that using a GPS navigation system to get to one's destination essentially switches off distinct parts of the brain, including the hippocampus. As the hippocampus is known to grow based on stimuli, it is also likely that it will decrease in size if not stimulated properly. However, no studies have been conducted to test if GPS use causes hippocampal atrophy (O'Connor, 2019).

3.3. Design features

Several features have been found to help cognitive map development:

3.3.1. Map orientation:

Map orientation has large effects on turn decision making and knowledge acquisition of an area (Rizzardo & Colle, 2013). There are two common types of map orientation in dynamic (moving) maps: Track-up orientation and north-up orientation. In a track-up map, the direction of travel is always upwards on the map. When making a turn, the map will rotate accordingly. Track-up maps have traditionally been superior when it comes to navigation efficiency, turn decision-making and level of mental workload (Rizzardo & Colle, 2013). Because of this, track-up maps have been the configuration of choice in automotive navigation, as the focus in Automotive HMI has been on usability and efficiency and their relation to navigational effectiveness or driving performance (Oliver & Burnett, 2008). These maps are useful for facilitating efficient turn-by-turn guidance, but the rotations of the map makes it difficult to learn the spatial layout of the environment (Rizzardo & Colle, 2013)

In a north-up orientation, north is always facing upwards on the map, and thus it is the user's icon that rotates on the map. The map orientation is constant at all times and does not rotate. These maps have been found to improve spatial knowledge acquisition, both in aircraft and in automotive settings (Rodes et al., 2009). These maps may make it easier to learn the environment because landmarks remain consistent and do not rotate, and because this type of map display more closely resembles traditional map information (Rizzardo & Colle, 2013).

The main problem with North-up maps is the cartographic misalignment that occurs when the direction of travel is not headed towards North. If a person is travelling south, then a turn against right on the map would have to performed as a turn against left in the real world. Most humans struggle to mentally calculate turn decisions when the there is a misalignment between the direction of travel and the map orientation (ibid.), which is problematic. According to Ross et al. (1996) any advantages of a north up display for this reason, are likely to be outweighed by the need for mental rotations.

As a result, north-up maps have traditionally been linked with a higher rate of navigation errors (Rizzardo & Colle, 2013). However, efforts have been made to counter this. Rizzardo & Colle proposed a Dual-Coded Advisory Turn Indicator for Maps (DATIM); A system where both spatial and verbal cues were used to help people calculate the correct turn decision. However, that experiment was based on pressing the correct arrow on a computer keyboard in a lab setting. In this experiment, a version of the DATIM system will be used to assist the participants with turning decision in simulator setting.

3.3.2. Landmarks:

One of the most frequently recurring design features in the literature is navigation based on landmarks. According to Philips (1999), landmarks are important environmental and navigational cues that aid drivers in navigating. Reagan & Baldwin (2006) found that using a landmark-based navigation system increased navigation performance and improved route memory without increasing the mental workload or adversely affecting driving performance. According to Philips (1999), landmarks improves navigation performance and lowers decision times.

4. Methods

4.1. Experiment design

The study was conducted as a within-subjects, repeated measures driving simulator experiment, inspired by and roughly based on Oliver & Burnett's 2008 study, but with a larger sample size (N=17). The participants were tasked with driving three different routes while following directions from three different types of navigation designs. The driving sessions took place in a heavily modified edition of the video game *Grand Theft Auto V,* and the interfaces were video animations played at the same speed as the participants were driving, simulating a fully responsive navigation system. Each participant drove three routes in random order, with each of the three interfaces, also in random order, for a total of nine possible combinations of route and interface.

fig. 1: The test environment for the simulator setup

After each route was driven, the participants were tasked with drawing the route they had driven on a paper map and marking the locations of landmarks they had driven past on each route. The participants were equipped with eye-tracking goggles to monitor their gaze metrics during their drive.

4.1.1. Research question & hypothesis

As described in the introduction, the primary research question is defined as follows: "Does the design of the map interface in a navigation system affect cognitive map development? Does the design of the map interface in a navigation system affect driving performance, and how much time is spent looking at the navigation system." The 3 null hypotheses are defined as follows:

- $H_0^{(1):}$ *There is no correlation between the three interface types and cognitive map performance.*
- $H_0^{(2):}$ *There is no correlation between the three interface types and driving performance*
- $H_0^{(2):}$ *There is no correlation between the three interface types and time spent looking at the interface*

4.1.2. Population

18 (12 females and 6 males) participants were recruited for this experiment. This was selected as it was a number that would multiply well with the number of conditions. All participants were to drive three different routes, which would create 6 runs for each condition on each route. There was no requirement to have a driver's license. The navigation skill level of the participants was recorded, but the driving skill level was not.

One participant was removed post-experiment due to errors in the data collection process. Participant recruitment was limited to staff and students at NTNU Gjøvik due to COVID-19, and neither the gender nor the age distribution is ideal.

4.2. Navigation interfaces

In this report, the term *navigation interface,* or just *interface,* refers to the design and behaviour of the map that the participants were tasked with following. For clarification, the term interface in this report does not refer to a user interface that can be interacted with. There are no menus, buttons or other objects that allows for interaction, only different ways of displaying map information. There are three different interfaces: rotating, hybrid and novel. These three interfaces are described more in detail below. The design of these systems are the independent variable for this project.

4.2.1. Rotating interface

A navigation system representing what one would expect to find in a vehicle today. The map is displayed directly top-down and with a head-up orientation. The map is rotating so that the user is always travelling upwards on the map, following the blue line (see *fig. 2)*.

fig. 2: The rotating interface

4.2.2. Hybrid interface

A map which is always rotated so that north is upwards on the map. To account for the increased workload associated with this orientation (especially when travelling southwards), turning indicators with both spatial and verbal turn information as described by Rizzardo & Colle (2013) were included. The map is compressed vertically to approximately 60 percent of the map's original height. This gives the map a sensation of space, and an isometric look that for a sense of three-dimensionality, as discussed on the next map type. In *fig. 2* we can see at cutout of the map at the same point in the same route as *fig. 1*. As the driver is now travelling southeast-bound there is use for the turning indicator to help the driver make the correct turning decision.

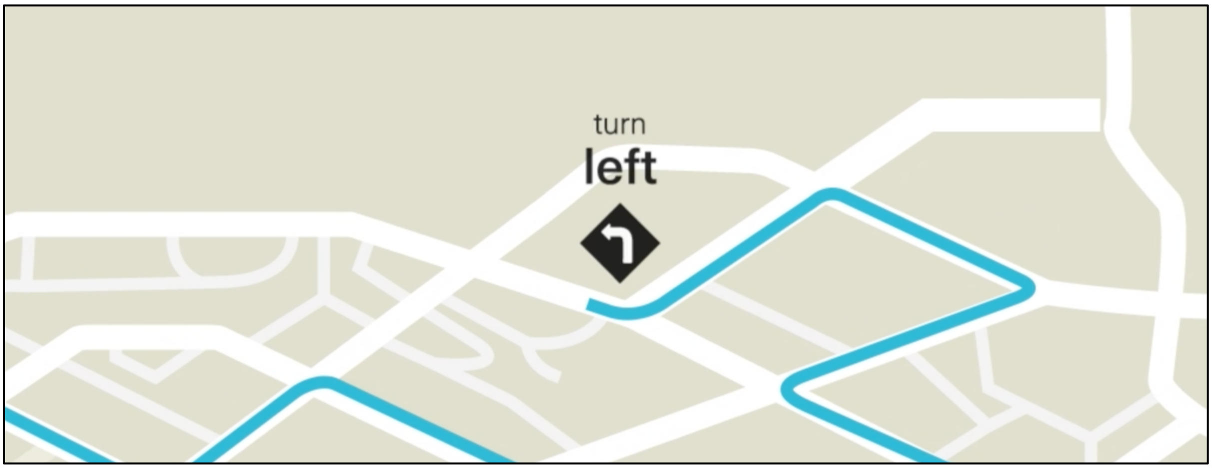


fig. 3: The hybrid interface

Landmark: A map which is based on the hybrid map but features 3D models and icons of landmarks on the map. Landmarks were aggregated from a landmark database located at *grandtheftdata.com*, and isometric 3D models were created for some of these. These models were placed on the map and displayed at 50% opacity so that the user could still see roads and routes behind such buildings. In addition, icons such as gas stations, churches, restaurants and parking facilities were placed on this map.

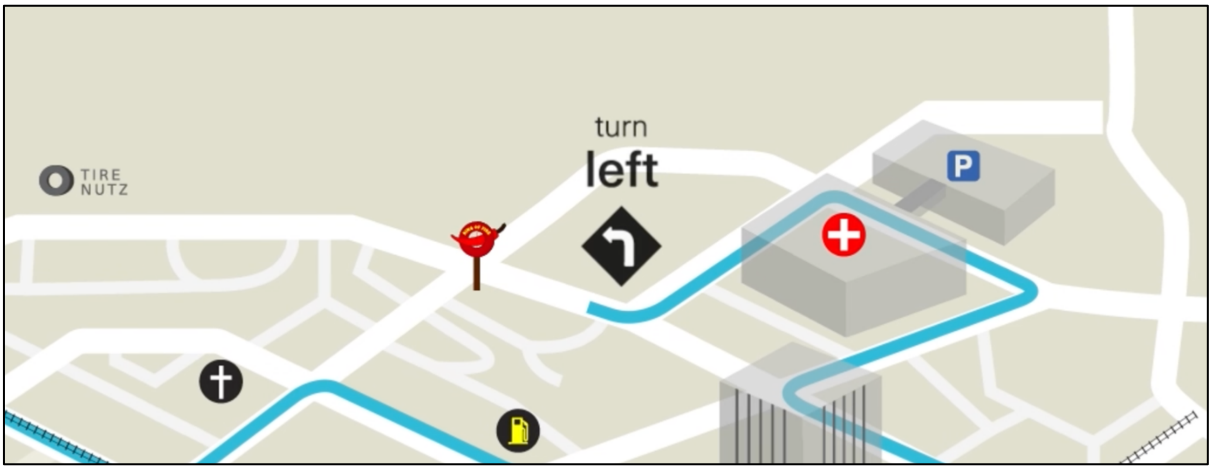


fig. 4: The landmark interface

For the sake of clarity, referrals and analyses of three interface types will be done in the order presented here. The interfaces are not referred to by numbers, but if they were, it would be 1 = rotating, 2 = hybrid, and 3 = landmark. The rotating and the landmark interface are the "main" interfaces in this experiment, with the rotating interface representing the map display that is commonplace in present-day vehicles, while the landmark interface represents a possible future design. The hybrid interface is mostly included for measurements and statistical purposes.

4.3. Driving simulator hardware

A low fidelity driving simulator was built at NTNU Gjøvik. The Simulator consisted of a Logitech G29 steering wheel, and a 3440x1440 ultrawide monitor powered by a high-performance desktop computer with a NVIDIA GeForce GTX1070 graphics card. In the experiment design process, initial tests were performed with triple and quad monitor setups. This was however discarded in favor of an ultrawide monitor, due to issues with motion sickness (simulator nausea). As driving activity is not what is measured or assessed, achieving a very high level of realism is not of high importance. However, it is important that the subjects can control the car as they are used to without spending a lot of time learning to control the simulator. The experiments were conducted in a room with controlled lighting, and a remote workstation for the researcher.

3.2.2. Navigation display

To act as the navigation system display, an Apple iPad was mounted to the base of the steering wheel. The navigation videos were displayed in VLC on a MacBook Pro which was then displayed on the iPad using a software called Duet.

4.4. Driving simulator software

Many considerations were involved in selecting the software used to run the driving test. Existing scientific driving simulator software intended for usage in sectors such as automotive engineering and city planning, e.g. STISIM (Systems Technology Inc.) and CarSim (Mechanical Simulation Corporation), was excluded due to cost and their requirement of specialized computer hardware paired with the software packages.

Since driving performance and extreme realism were not of high importance, initial trials were performed in three different software programs: Euro Truck Simulator 2 (SKS Software, 2012), City Car Driving (Forward Development, 2007) and Grand Theft Auto V (Rockstar Games, 2013). Both City Car Driving and Euro Truck Simulator features large game environments, but these environments are generic and empty, and lacks content beyond the road network and some generic buildings and cityscapes.

Due to this, Grand Theft Auto V, hereafter referred to as GTA V, was chosen to act as the environment for the driving sessions. GTA V features a very large and lifelike game environment and is rich with features, landmarks and buildings, and as such, were very suited for the driving sessions. The Grand Theft Auto video game series is somewhat infamous for depiction of criminal activities and other types of antisocial behaviour, but the game was modified to suit the requirements of this project: All traffic, random events and pedestrians were removed from the game. To ensure the same driving conditions for all participants, dynamic weather and time of day features were disabled. All participants were set up in the same vehicle, a small sedan which represented a regular family car. The game does not natively support steering wheel controls, but a modification was installed to incorporate this.

4.5. Navigation software design

Originally, the plan was to use a navigation system that is fully responsive. This means that the participants position and action in the virtual environment would be updated on the navigation interface in real time. However, no solution currently exists for prototyping navigation interfaces. This means that a solution like this would require a software development process, which there was a lack of resources, programming skills and time to conduct.

Instead, animations were made to imitate the appearance of such a system. Map files (inspired by a map created by artist Guy Douglas) and landmark models were created in Adobe Illustrator, and imported into Adobe After Effects, where the maps were animated to follow the routes. In total, 9 different animated routes were created. The colour scheme for the maps was sampled from Google Maps, but the background was slightly darkened to increase contrast between the road network and the background.

4.5.1. Syncing driving behaviour with navigation animations

Probably, the most challenging aspect of the entire thesis process was syncing the driving guidance with the actions of the driver. Initial attempts of manually manipulating the video playback speed as the driver accelerates or decelerates were highly unsuccessful and resulted in a complete loss of connection between the navigation guidance and the driving actions.

This was solved by limiting the vehicle speed and editing the length of the animation videos to the estimated time spent driving the routes. A modification called *Enhance Cruise Control* (2015) was added to game, which allowed the game to set a constant speed of travel. The vehicle speed was set to 40km/h, as this was found to be a velocity where the participants were able to make turns without slowing down beforehand. Except for a small acceleration period (ca. 2 seconds) the car held this velocity for the entire duration of the drive.

To find out how long each video should be, each route was driven three times at this speed. The average time spent driving each route was set to be the video length, and the animations were stretched to this desired length in Adobe Premiere Pro.

Based on driving style (especially cornering radius), there is a possibility that the driver gets behind or in front of the navigation animation by a few seconds. However, this was not problematic, and participants reported that they felt the navigation system was fairly responsive and in sync with their driving. In addition, the researcher had the option of briefly changing playback speed, pausing or skipping the video to increase the sync level, something which was done occasionally.

4.5.2. Navigation mistakes and crashes

Another problem with using a video-based approach for the navigation interface is that an eventual crash or navigation mistake would lead to a complete disconnection between the navigation guidance and what is experienced in the virtual world. This was solved very pragmatically; in cases where participants crashed or made navigation mistakes, they were verbally instructed where to drive in order to get back into their route as fast as possible.

4.5.3. Route selection and design

As the experiment was performed as a repeated-measures design, the routes could not be in the same area of the virtual environment. The participants would be subject to the learning effect, and therefore perform better on their later laps. Because of this, each route was located in a different area in the virtual environment.

The three routes (northern route, southern route, and western route) were named after their location in the virtual world, and they featured widely different features and landmarks. One route were concentrated around low-rise buildings in a rectangular city grid (South), one featured a varied cityscape with canals, high-rises and parks (West) and one featured an upscale residential area with mansions and a golf course (North). These different areas were chosen to minimize the possibility of eventual results being skewed by a certain cityscape or geography. The map interface needs to work in various settings and scenarios.

The routes were defined to meet some predetermined criteria: There were to be no overlapping route segments, as the route animations was not designed to accommodate this. Efforts were also made to keep the routes of equal difficulty, and all routes were also (within 10%) of roughly the same length.

4.5.4. Eye-tracking

To record gaze data, and first-person video footage of the driving sessions, participants were equipped with eye-tracking goggles from Senso-Motoric Instruments (SMI). As the eye-tracker is intended for short sessions of up to 5 minutes, while in this experiment the sessions lasted approximately 30 minutes, issues with battery usage and storage space were challenging. The length of the footage was also problematic when analyzing the videos, as the SMI BeGaze software did not handle the large file sizes of these recordings particularly well.

The data from the eye-tracker was analyzed in SMI BeGaze, where an AOI (Area of Interest) were created from the iPad screen. Dwell time (amount of time spent looking at the screen), number of fixations and average fixation length for every participant was then gathered. No personal data in the form of pupillometry or video footage of the participants eyes were recorded.

4.6. Drawing task

After each route, participants were asked to draw the route they had been driving and place landmarks from the driven area on the map (see fig. 3). One common method for measuring cognitive maps is called sketch mapping, as described in Kitchin (1999), and performed in both Burnett & Lee (2005) and Oliver & Burnett (2008). The most common way of measuring cognitive maps is by making the participants draw a paper version of a location. This experiment uses a modified type of sketch mapping, as the routes and environments are too complex for participants to be able to recreate it freely based on one short driving session.

Participants were given three minutes to complete each task, which took place directly after completing the driving session. The participants were given three tasks: “Draw the driven route on the map”, “draw lines from the images of landmarks on the page to where you think these are located on the map”, and “shade areas with water, park areas and place eventual extra features such as tram/train lines.”

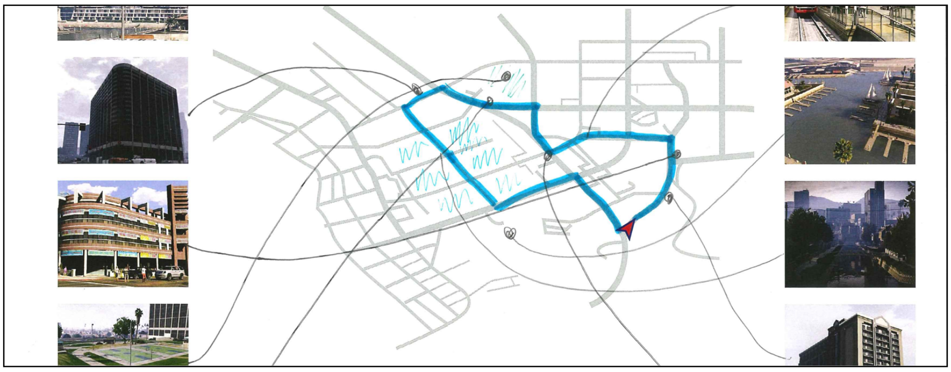


Figure 3: An example of a completed drawing task

4.6.1. Rating

The drawings were rated by the researcher based in two categories: route recreation accuracy and landmark accuracy. To improve validity, an interrater setup where scores from several independent raters is averaged into one score would be optimal. This would minimize rater bias, and eventual skewness between the importance of different rating criteria. However, this was ultimately discarded as ensuring that all raters had the sufficient area knowledge to correctly rate the drawings was a very complex and time-consuming task that this experiment did not allow.

As the ratings were performed by the researcher, efforts were made to minimize effects of confirmation bias, as well as possible bias by the researcher on what is important in scoring the drawings. All drawings were given a random three-letter code and shuffled before the rating process began. This meant that the rater was not aware of which participant or navigation condition that belonged to each drawing. Even though the rating process is subjective, the rating criteria for each category was operationalized in the following way:

Landmark placement accuracy: In this test, 1 point was given for each of the 10 landmarks on the page that were correctly scored. Participants were also asked to fill in eventual other extra features on the map, such as parks, water and trainlines, but as these features are hard to quantify, they were discarded for the sake of operationalization. Even though placing many landmarks incorrectly may indicate low knowledge about the area, this was not taken into account when calculating the scores, thus no minus points were given.

Route recreation accuracy: In this category the drawings of the driven route were compared to the correct one. While software to mathematically compare the deviation of these routes to the correct route may or may not exist, that approach were too time-consuming and labour-intensive. Instead, the routes were rated subjectively on a 6-point scale.

0: No understanding of the travelled route
1: Very weak understanding of the travelled route
2: Weak understanding of the travelled route
3: Some understanding of the travelled route
4: Good understanding of the travelled route
5: Recreated the route perfectly

4.6.2. Ethical considerations

There were few or no ethical concerns about this experiment. Eventual physical or psychological harm could only arise due to an unintended workplace accident. No personal data, apart from names, was collected, and the eye-tracker did not record data such as pupillometry or video footage of the participants eyes. The names of the participants and their corresponding ID have been saved in a file in a separate location, in case a participant wants to withdraw from the project. This file is only accessible by the researcher. All participants were required to be legally and physically able to drive, although not all participants had driving licenses

4.6.3. Infection control

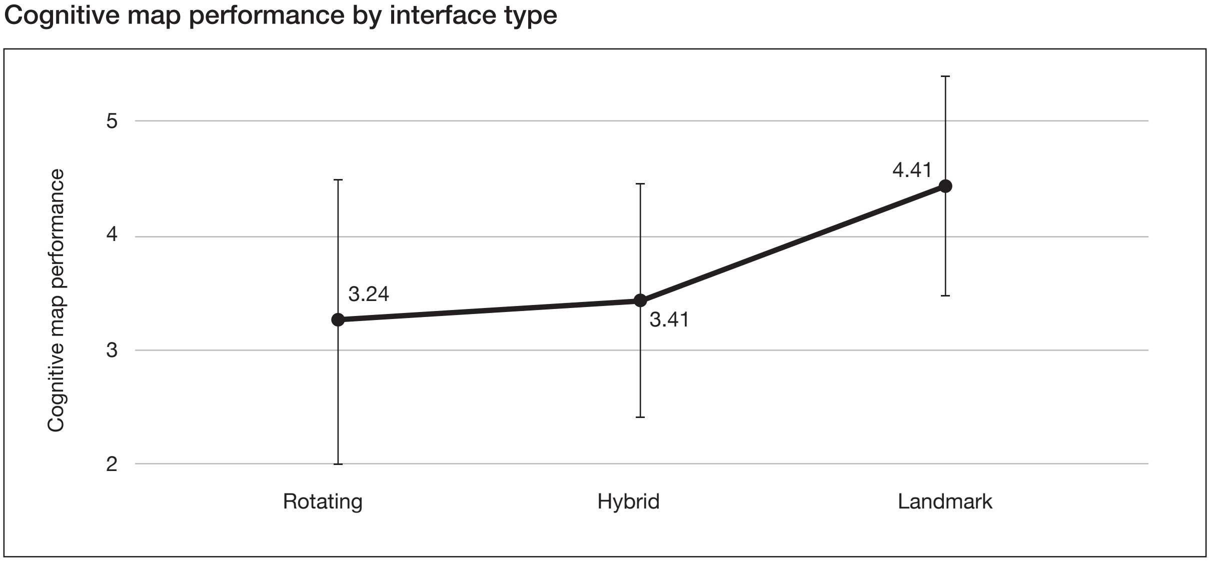
Due to the COVID-19 pandemic conducting an experiment with several participants meant that extra measures had to be taken to ensure maximum safety. All touchpoints were wiped down between sessions, and facemasks were used by participants and the researcher. A separate desk with a monitor and a wireless keyboard and mouse, allowed for remote launching and control the of the driving routes while keeping distance in accordance with university and national guidelines.

4.6.4. Analysis

Data from the drawing task and the eye-tracker were analyzed using SPSS software. Most analyses were performed using a General Linear Model Repeated Measures procedure. This allows to see both within-subjects and between-subjects effects in a repeated measures design. The cognitive map performance data, driving performance data, and the eye-tracker data was used as the within-subjects variable, while variables such as gender and navigation skill were used as between-subjects factors. In the graphs located in the results chapter, the error bars represent the 95% confidence interval.

5. Results

To make it easier to see the effects of each condition, the scores for the landmark test and the route recreation test were combined into a new variable called *cognitive map performance*. The mean score for all participants and interfaces is 3.38 (SD: 2.42). The mean cognitive map performance of each interface is 3.38 (SD: 2.42), 3.44 (SD: 2.06), and 4.43 (SD: 1.93) respectively. There is a moderate but not significant increase in cognitive map performance from the rotating to the hybrid to the landmark interface. The difference is larger between the hybrid and the landmark interface, and this difference is approaching significance (p = 0.58). Generally, this points to that a landmark-based, north-up map interface might increase cognitive map development, but given the large standard deviation, we can see that this is also very individual.



Cognitive map performance by interface type

fig. 5: Line graph of cognitive map performance by condition.

5.1.1. Route recreation performance

This was the task where the participants were to draw the route they had driven on a map, and there was a high level of variance in the scores. Across all three interface types we saw participants being able to draw the route perfectly, as well as not at all. Maps rated both 0 and 10 were found in every condition, indicating a wide range of performance by the participants. Distribution was quite even, which may indicate that difficulty of the route recreation task was fair but challenging. The north-up interfaces had higher mean scores than the rotating interface, but results did not reach significance. On a 0 to 5 scale, the rotating, hybrid and landmark interfaces had mean scores of 2.37 (SD: 1.46), 2.56 (SD: 1.32) and 2.75 (SD: 1.53), respectively. No significant differences in mean scores between genders were observed.

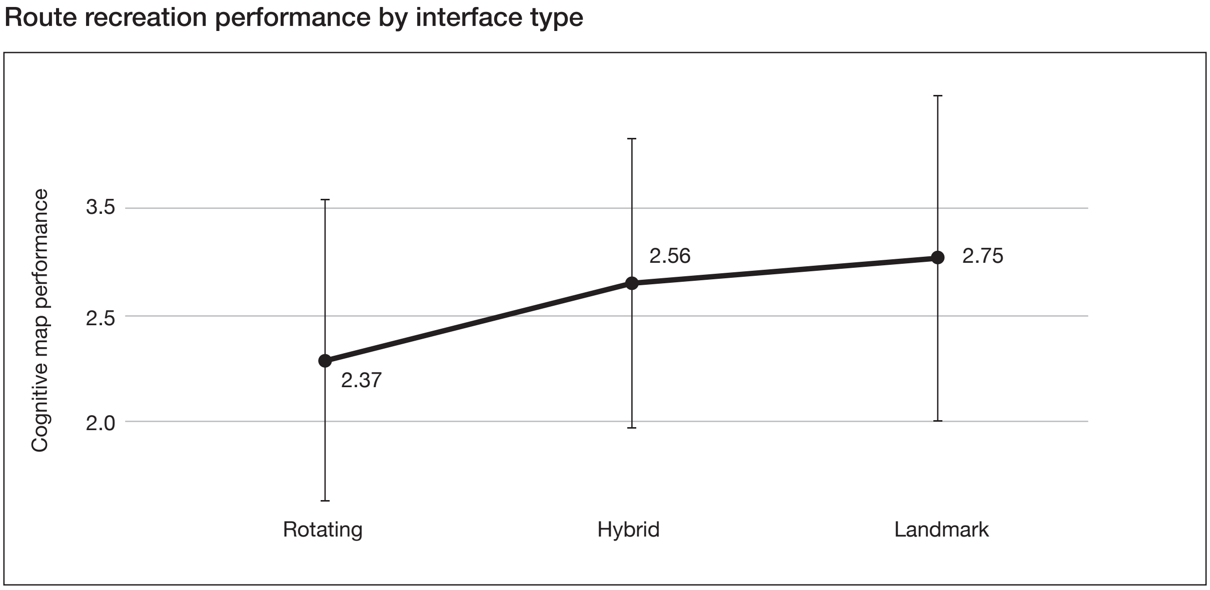


fig. 6: Line chart of route recreation performance by condition.

5.1.2. Landmark placement performance

On the landmark placement task, overall performance was low. On a scale from 1 to 10, no map got more than 4 points, and over 50% of the maps in every interface type was given a score of 1 or 0. This indicates that the task was too challenging for the participants. The rotating, hybrid, and landmark interface saw mean scores of .91 (SD: 1.30), .76 (SD: 1.03), and 1.65 (SD: 1.12). In this task, the between-subject effects between the landmark interface and the two others was significant (F = 5.099, P=0.12).)

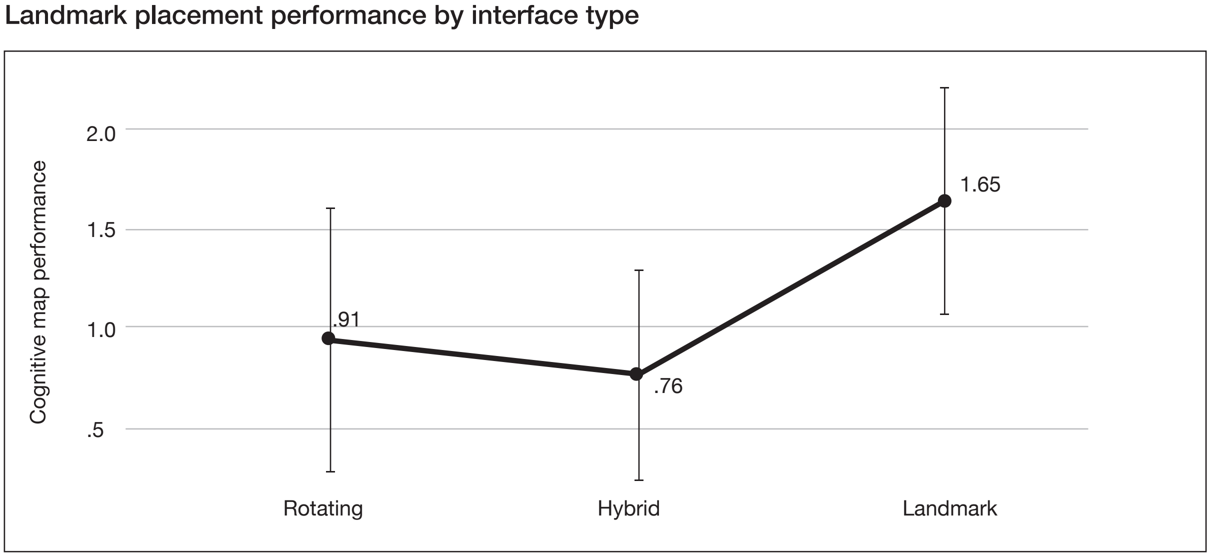


fig. 7: Line chart of landmark placement performance by condition.

5.1.3. Self-reported skill level and performance

In this section, the main focus is on how participants of different skill levels respond to the various interfaces. The scores from the participants' self-reported sense of direction and navigation skills were combined into a new variable, called *skill*, and then split into two groups of roughly equal size; *skill_low* (N: 9) and *skill_high* (N: 8).

There is a significant correlation between the subjects self-reported sense of direction and their route recreation performance (Pearson correlation coefficient = .424). Subjects who ranked their sense of direction as 5 out of 5 scored the highest on the route recreation task, and the three subjects who self-reported a sense of direction score of 1 (the lowest) scored zero points on the route recreation task. This is also true for the self-reported navigation skills score.

Sense of direction	*N*	*Mean cognitive map performance*	*SD*
1	1	0.00	.
2	4	2.25	2.63
3	3	4.00	2.65
4	8	3.38	1.96
5	1	7.00	.
Total:	16	3.38	2.41

Navigation skills	*N*	*Mean cognitive map performance*	*SD*
1	0	.	.
2	1	0.00	.
3	6	2.83	2.93
4	7	3.57	1.99
5	3	4.33	2.30
Total:	16	3.23	2.41

fig. 8: Cognitive map performance based on sense of direction and navigation skills

In general, we see that those who reported to have a high skill level also respond better to the novel interface type. In the low skill level group, the mean cognitive map performance rises from 2.89 (SD: 2.93) to 3.55 (SD: 2.01). In the high skill level group, the mean performance increases from 3.63 (SD: 1.77) to 5.38 (1.19). This increase in performance for the high skilled group is statistically significant (F: 4.73, p = 0.46), and there is also a significant difference in performance between these groups (F: 5.00, p = .041). There is an interaction effect between skill level and cognitive map performance. As one can see in the figure below, the high skill group takes a dip for the hybrid condition, while the low skill group sees a small hike. The reason for this is not quite clear but may indicate that the study population is not of sufficient size.

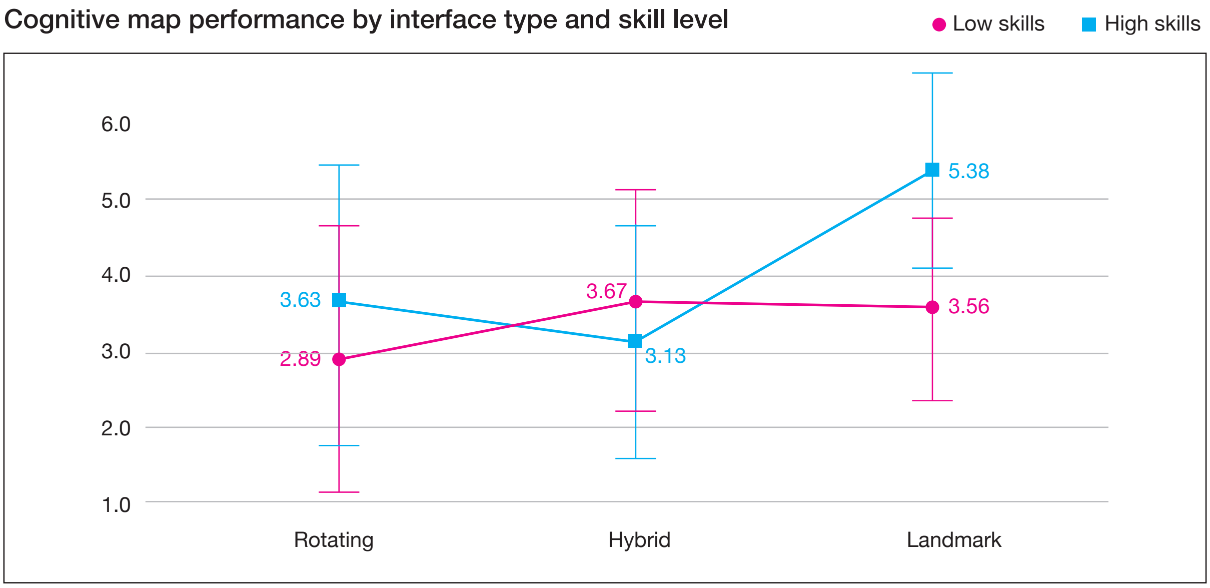


fig. 9: Cognitive map performance by interface type and skill level

5.2. Driving performance

In addition to cognitive map performance, the driving performance of each participant was analyzed from observations during testing, and from post-hoc footage obtained from the eye-tracking glasses. As the participants were using cruise control and there was no traffic or traffic rules to obey, driving performance is based on navigational mistakes or traffic accidents.

76.5% of all participants made some form of mistake, and the mean number of mistakes were .25, .31, and 1.00 for each of the three interfaces. The between-subject effect between the landmark interface and the two others was highly significant (p =<.001). This indicates that the increased amount of information in the landmark-based navigation system may lead to confusion for the driver. In contrast to other observations from this experiment, variables such as gender or skill level did not affect the number of mistakes, or how they were distributed across interfaces.

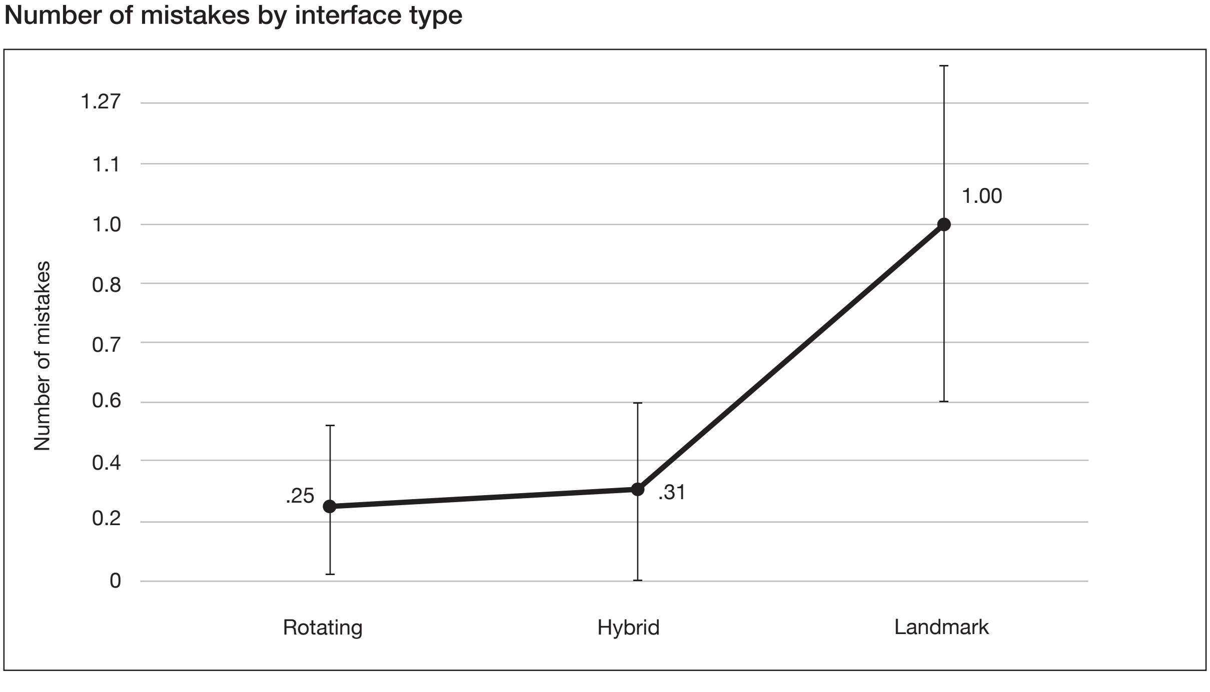


fig. 10: Line graph of number of mistakes by interface type

5.3. User ratings

5.3.1. Subjective interface rating

After the completion of all three laps, the participants were asked to rate each of the three navigation interfaces. This task was met with some confusion, as some participants did not remember the differences between the maps. On a range from 1 to 5 the total mean was 3.38, and the mean for the three interfaces were 3.71 (SD: 1.05), 3.12 (SD: 1.05) and 3.35 (SD: .79), respectively. The large standard deviations shows that there is a high level of variance in individual preferences and may indicate that users prefer head-up oriented maps, but no significant results support this. The hybrid interface is rated the lowest, which may be because it lacks any clear advantages in comparison to the two other interfaces.

Subjective interface rating

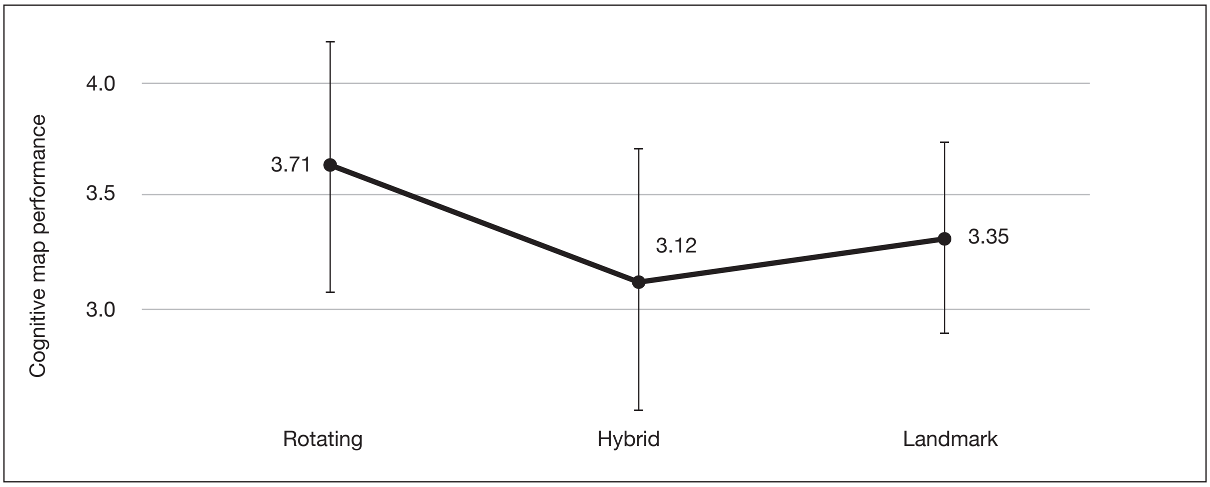


fig. 11: Line graph of subjective interface rating by participants

5.4. Gaze data

Post-hoc analysis of the eye-tracking data enabled the visual demand of the three interfaces to be compared by measuring glance behaviour. From the BeGaze software, three measurements were extracted: *total dwell time, number of glance*s and *average glance duration*. The most interesting variable of these is the time spent looking at the navigation interface (dwell time), as time spent looking at this interface is time spent not looking at the road. This may have implications for road safety, which is discussed more in detail in the discussion chapter.

On average, 18.46% of the time was spent looking at the navigation interface. The rotating, hybrid and landmark interface types saw dwell time means of 16.44% (SD: 5.81), 18.52% (SD: 6.18), and 21.09% (SD: 6.96), respectively (see fig. 14). The dwell time increases with over 28% from the rotating interface to the landmark interface, and the difference between the rotating and the landmark-based interface is significant ($p = .003$). A significant increase of fixation counts ($p = 0.32$) is also observed across the three conditions (see fig…). Fixation duration does not increase by much, which is as expected, due to the relatively fixed nature of eye movements, where the vast amount of fixations are located in the 150–250 ms range (Galley et al., 2015).

		Dwell time			*Fixation count*			*Avg. fixation duration (ms)*	
Condition	1	2	3	1	2	3	1	2	3
Mean	16.44	18.52	21.09	167.53	181.13	220.00	201.00	202.27	208.45
Median	16.10	18.90	20.3	162.00	184.50	207.50	193.70	204.00	215.00
Std. Dev.	5.81	6.18	6.96	47.63	56.28	69.08	37.08	29.01	26.13

fig. 12: Table of eye-tracking results

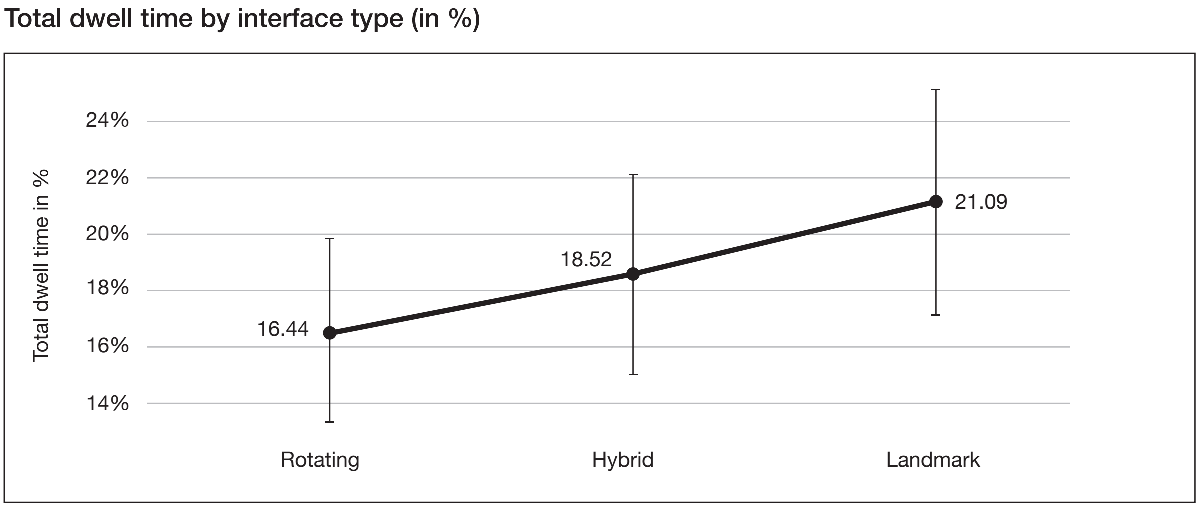


fig. 13: Total dwell time by interface type

Several differences between genders and skill levels were found in the results. Males were found to spend longer time looking at the interface (19.86%) than females (17.96%). Males exhibit a larger span of mean gaze dwell time than females; while the male participants had a mean increase of 8.56 percentage points from condition 1 to condition 3, female participants had a mean increase of 3.30 percentage points. Males also exhibit a wider standard deviation, something that may indicate that there are larger individual differences in males when it comes to dwell time. Again, all within-subjects effect are highly significant, but differences between the different groups does not reach significance.

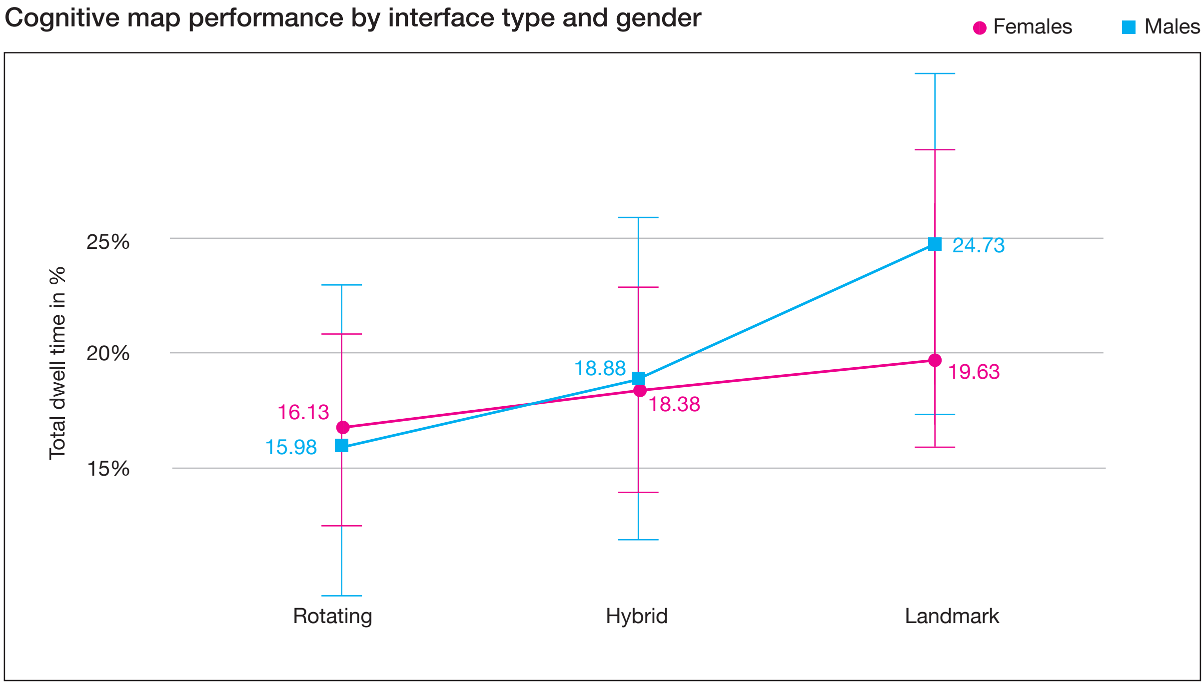


fig. 14: Total dwell time by interface type and gender (in %)

	Total	*Condition 1*	*Condition 2*	*Condition 3*
mean male dwell time	19,87	15.98	18.88	24.73
mean female dwell time	18.21	16.62	18.38	19.63
mean low skill dwell time	18.84	17.43	19.44	19.67
mean high skill dwell time	18.51	15.44	17.60	22.50

fig. 15: Table of total dwell time by gender and skill level

6. Discussion

6.1. Experiment facilitation

Overall, this experiment was facilitated successfully, and it could serve as inspiration for undergraduates and small businesses on how to perform automotive HCI research on low budgets. Using a role-playing video game such and Grand Theft Auto V for HCI research is an unconventional approach, but with the animated videos it was successful, and verbal feedback from participants stated that they found the simulation to be realistic. Some participants gave feedback stating that they felt the navigation animation was so realistic and well-timed, that they had to remind themselves that it was only video.

Ideally, the study population (N =18) should be larger and more diverse in forms of age and gender and even geographic distribution. However, each experiment was fairly time-consuming, and the Covid-pandemic did make it difficult to find participants who were not staff or students at NTNU. Considering this study population is adequate.

6.1.1. Rating & Testing

The main area of improvement is the rating and testing procedures. Most importantly, the drawing task was not optimal for measuring cognitive map data. In order to mitigate the learning effect, the participants had to be informed beforehand about their objective to place landmarks on the maps and draw their travelled route. Naturally, this changes the participants awareness during their drive, and it is likely that at least some of the participants actively scanned and the area for landmarks to remember while driving. This is a type of behavior that is not very common.

This issue is supported by comments from participants, stating that they would never study the area of travel like they did in this experiment. In addition, the drawing performance is further influenced by factors such as previous map knowledge, drawing skill, and even effort. However, correctly measuring cognitive maps is difficult (as outlined in Blades (1990)), and sketch mapping exercises, like the drawing task in this experiment, are still seen as efficient and feasible ways to do this.

6.2. Performance

In the results from this experiment, one can see that the hybrid and novel interfaces have higher cognitive map performance than the rotating map display. One can also see that this effect is not statistically significant, and that there are several drawbacks to the hybrid and novel interface types.

6.2.1. Largest difference between hybrid and novel interface

The large difference between the results of the hybrid and the novel interface was surprising. These two interfaces were designed to be fairly alike, and both were designed to differ drastically from the rotating interface. However, in the results we can see that the rotating and the hybrid interface were fairly close, while the landmark interface saw greater increases both in performance and number of mistakes. One cause for this may be that the turning indicators were helpful when they were prominent on the map, but that when participants were presented with extra information in the form of landmarks and businesses, the participants lost focus from the turning indicators. This may indicate that the third interface introduced a form of information overload for the participants, where the increased amount of information actually has a negative effect on the participants. Future projects could explore if e.g. the turning indicators could be replaced by changes in audio, lighting, or tactile feedback.

This can also be seen from the participants subjective rating of the three interfaces; both the hybrid and the novel interfaces were rated lower than the rotating interface, and many participants gave feedback saying they found the north-up perspective confusing, and that they preferred rotating maps

6.2.2. Map rotation and turning assistance

Researchers such as Rizzardo & Colle (2013) claims that north-up-oriented maps is a necessity for effective spatial learning and cognitive map development. The results in this experiment show a small, but not statistically significant, increase in cognitive map performance after driving routes with north-up displays. As navigating efficiently and safely is arguably more important than cognitive map development, the results from this experiment does not support the view that north-up map displays are developed enough to replace track-up maps as the main display mode in vehicles.

The turning indicators were found to be useful, Participants also said that they found the turning indicators useful, and some participants said that they relied singlehandedly on these during the entirety of their driving session. One flaw with the experiment design is that no map interface was designed with a north-up map orientation but no indicators. This makes it impossible to quantify what effect the turning indicators had on turn decision making.

6.2.3. Navigation skills and cognitive map performance

One of the most interesting findings was the one related to skill. The participants who ranked their own sense of direction and navigation skills the highest, performed better. More importantly, they saw a larger increase in cognitive map performance. This might indicate that those who already are skilled navigators are able to utilize extra navigational information, and thus gain more knowledge from the novel system.

Many participants found the landmarks useful and stated that they were helpful not only for the drawing task, but also that they were useful for helping them make the correct turns. Considering that the number of mistakes were significantly higher when navigating after the landmark interface, this may or may not be the case.

In conversation with the participants, it appeared that the participants who were using the extra information, did not use it for navigational decision-making, but as an extra reference/backup to verify their own wayfinding decisions. This is a possible explanation for why the already skilled navigators are able to draw advantage from the new system: The extra information provided by the novel interface is mostly useful if you want to take an active part in the navigation process. Some people cannot, and do not want to take this active role, and thus, they do not utilize this extra information.

6.2.4. Driving mistakes

In the experiment we saw that the novel interface leads to large increase in the amount of driving mistakes. The novel interface led to 4 times as many mistakes as the rotating interface, and three times as many mistakes as the hybrid interface. These effects are statistically significant in and across all groups. In contrast to the cognitive map performance, the high skilled group had the same increase and amount of mistakes. Future research needs to address these issues if an implementation of such a system is to be discussed.

6.2.5. Gaze data

The driver has only one visual channel which must be time shared. This means that any secondary task which uses the visual channel of the driver will reduce the time available for driving (Ross et al., 1996). Automotive researchers should aim to minimize time spent looking at any secondary tasks, such as the navigation and interface system.

Considering this, it is problematic that there was a significant mean increase in total dwell time of over 28% from the rotating to the landmark interface. As successful driving performance is heavily dependent on uptake of visual information, it should be discussed whether this increase is acceptable for automotive applications.

6.2.6. Future work

A natural step forward would be focusing on the interaction effect between skill level and cognitive map performance. As we have seen that skilled navigators benefit more from additional information, work could be conducted to explore a navigation system that dynamically adapts to the skill level of the driver. An experienced and comfortable driver would receive less guidance, but more information about landmarks and the environment, while a driver that is not as comfortable and secure in the navigation task would receive more direct navigation guidance.

6.2.7. Conclusion/final comments

This experiment supports the view that cognitive map development can be improved by changing the features and design of a navigation system. This results from this experiment shows that using a north-oriented map with landmark information leads to a moderate increase in cognitive map performance. People who consider themselves to be skilled navigators benefit more from a navigation system with more information, while people who do not consider themselves to be good at navigating is not able to efficiently utilize this extra information.

However, this increase in cognitive map development comes at a cost. In this experiment we saw a significant increase in driving and navigation mistakes, as well as increased amount of time spent looking at the navigation interface, which is problematic in an automotive setting. Before map interfaces to increase cognitive map development are implemented in vehicle navigation systems, these issues need to be eliminated.

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