MASTER THESIS

The effect of infrastructural nudging on cyclist route choice

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Preface

This report is the culmination of 6 months of hard work. I am very proud of what I have achieved and hope that it will be a delight to read. I feel like this research has not only brought to light a topic which is very much under researched. It has also sparked a research minded spirit within me for which I am very glad. I have to say that although I am not a researcher type, it will be hard to not perform further research into the gaps that I have found. I want to thank all my supervisors. I want to thank Yan Feng, for showing me the wonderful world of VR. I want to thank Maarten Kroesen for trusting me, even though he was not fully convinced at first. I want to thank Jacob Tielemans for his immediate enthusiasm, and I want to thank Dorine Duives for reminding me to get some sleep from time to time. I also want to thank Arco van Beek, for all the great advice he gave early on. I want to thank the whole Royal HaskoningDHV for allowing me to see how an engineering firm works and for all the advice they gave. I want to thank the XR Zone team for always being available to spar with if I had a question about my VR environment. I want to thank Dion Mol for keeping me motivated when I felt down. Finally, I want to thank Jenny van Lienden for always supporting me when I needed it most.

Abstract

Cyclist route choice can lead to uncomfortable and dangerous situations. Therefore, it is important to research ways to influence this. This study explores how infrastructural nudging can be used to influence cyclist route choice. Using virtual reality and a physical bicycle setup the impact of visual road hierarchy, visual obstruction and herding through street art is studied. A virtual urban environment was designed with 11 T-intersections. In 9 of the 11 intersection these methods were applied in three different ways, to see whether the nudge impacted cyclist route choice. The gathered data was then analysed with descriptive data analysis and discrete choice modelling. This study shows that cyclists follow nudges using visual road hierarchy and herding. However, they do not follow nudges with visual obstruction. This effect seems to be the same for people of all ages, genders, heights etc. Though less experienced cyclists seem to react more heavily to obstruction methods. The results also indicate that cyclists have a significant right-handed tendency. This effect is not influenced by eye or hand dominance. The effect becomes slightly weaker when nudging is applied but does not go away. Future research should validate these results in a physical environment before this is used in practice.

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Executive summary

Cyclist route choice can lead to uncomfortable and dangerous situations. Even though research into the safety of vulnerable road users has been steeply increasing there are still parts which are overlooked. Research mostly focusses on safety whilst cycling a certain route. Route choice itself can be a catalyst to accidents as well. People's choices can be influenced in three different ways: Incentivising, informing, and limiting the choice space (nudging). Incentivising and informing are used a lot in practice already, but research into nudging has been lacking.

The aim of this study is to explore the ways infrastructure can improve cyclist route choice behaviour with nudging. This aim is reached by performing a Virtual Reality (VR) enforced stated choice experiment with a bicycle simulator. The study specifically looks at T-intersections in urbanised areas, since it is expected to be most useful there.

A thorough literature review finds 9 promising possible intervention based on psychological theories and previous practices in the fields of urban planning, environmental science, nutritional science, and economics. The 9 methods can be found in section 2.5. Together with Royal HaskoningDHV the 3 most promising methods are selected to test in an experiment. These include blocking the view of one of the directions with object such as trees and bushes (obstruction), implying a hierarchy in the road structure with road markings (hierarchy), and using art depicting humans and other creatures moving in a certain direction, to guide people with herding behaviour (herding). Each method got split into three variants, to check the effectivity of different versions. This can be read in section 3.3.2.

Figure 1 Obstruction (left), hierarchy (middle), herding (right)

In the VR environment a street is modelled to resemble a generic 2-way shared street as presented by the CROW. The main street is 5.8 meters wide and both sidewalks are 2.4 meters wide.

Figure 2 Experiment setup

Participants were put on a bicycle simulator and had to cycle through 11 intersections. These intersections include the 9 variants and 2 times the base situation without any nudging present. Cyclists were immersed as much as possible, by allowing them to cycle physically and even introducing multisensory input such as wind blowing in their face. They could not turn the bike physically but could make turns by pressing buttons on the handlebars. More info on the construction of the environment can be found in section 3.3.3.

The experiment is analysed with descriptive analysis in SPSS statistics and a multinomial logit model in Rstudio. This analysis found which nudging method work best and what personal characteristics influence this effectivity.

Personal characteristics have almost no effect on cyclist route choice. Characteristics like age and gender do not influence the effectivity of the nudging methods. This means that nudging work the same regardless of the target demographic. Cyclists do, however have a directional bias. When no nudging is applied cyclists turn to the right 62% of the time. This means that nudging people to the left will always be harder than nudging people to the right. This directional bias is also not influenced by any human characteristics.

This study has found that obstruction is not an effective method for nudging. Cyclists interpret these forms of nudging in all kinds of different ways, therefore making their effect unpredictable. Placing a tree on a side of the road, slightly attracts cyclists but not significantly enough to be advised. Less experienced cyclists are slightly more affected by this form of nudging.

Hierarchy is an effective form of nudging cyclist route choice. Using a white curve or white truncations on the road very actively nudges cyclists in that direction, up to 75%. Making the road a different colour does not significantly influence cyclists. This last variant is often use in infrastructure design, but this study suggests that it is not effective. It could be that the contrast between the two road colours was not high enough, but still it is advised to take a closer look into the effectivity of this method, and refrain from using this method until its effectivity is proven.

Herding is also an effective form of nudging cyclist route choice. It successfully nudges cyclists up to 65% of the time. It is advised to use imagery of humans, since it is hypothesised that humans react more strongly to depictions of humans, rather than animals or other objects.

In general, this study concludes that nudging can be a powerful tool to guide cyclist travel flows. However, it is exploratory in nature, so the findings should be tested in a physical environment before using in practice.

1 Introduction

1.1 Problem definition

Cycling is a very common means of transport. In the Netherlands it is the second most used mode of transport, just behind the car (CBS, 2021). To ensure safety and comfort, it is important to have sophisticated infrastructure and well laid out rules.

In the last 5 years fatal cycling accidents have been rising sharply (NOS, 2023). This rise is mostly seen in the elderly community. The rise in fatal accidents raises the need for better research and guidelines. Especially now that bicycle use is increasing drastically throughout the world. Since the corona epidemic bicycle use has been skyrocketing in almost every country (Bernhard, 2020). With the Netherlands being the frontrunner in bicycle research it is important to expand our knowledge as much as possible to provide a well-built cycling infrastructure in the rest of the world.

Even though research into the safety of vulnerable road users has been steeply increasing (Scarano et Al, 2023), there are still parts which are overlooked. Research mostly focusses on safety whilst cycling a certain route. Route choice itself can be a catalyst to accidents as well. (Mesimaki, 2021) state that most pedestrian cyclist (near) accidents occur on pedestrian streets. Cyclists being in unfavourable places pose a threat to safety and efficiency and should therefore be avoided as much as possible. One such example is the intersection of the Kruisstraat and the Barteljorisstraat in Haarlem.

Figure 3 Intersection of the Kruisstraat with the Barteljorisstraat

In the street depicted in Figure 3 cyclists are compelled to go through the busy Barteljorisstraat (the middle street) to go to the Grote Markt even though it is forbidden for cyclists. Cyclists should go through the Krocht (the right street) but are currently not doing so. Influencing the route choice of cyclists in such a situation can prove to be a big asset.

People's choices can be influenced in three different ways (Hansen, 2016). Incentivising, informing, and limiting the choice space (nudging). A plethora of research investigates the effects of incentivising and informing, but research into the effects of nudging has been lacking.

Nudging is a form of limiting people's choice space without them knowing. In a cafeteria for example, the unhealthy snacks can be laid behind the fruits, so people are enticed to grab the fruit. This research explores whether this form of nudging can be used to influence cyclist route choice.

1.2 Research question and objective

The objective of this research is to explore the ways infrastructure can improve cyclist route choice behaviour with nudging. This is achieved by answering the following main research question:
How can infrastructure be used to nudge cyclists to make specific route choice decisions?
The main research question is jointly answered by the following sub-questions:

1. What factors influence route choice according to literature?
2. How can the effects of nudging techniques effectively and efficiently be measured?
3. Which infrastructural interventions can be taken to nudge cyclist route choice?
4. What is the impact of infrastructural interventions on cyclist route choice?
5. What participant characteristics influence the effect of nudging on cyclist route choice?

1.3 Scope

For this research some boundaries are set up to make the scope approachable and achievable. The research will look at T-intersections in urbanised areas. For the experiment only one location is chosen to limit the scope. This location will be a T-intersection since these intersections are most common and most straight forward to apply nudging interventions. The T-intersections are placed in urbanised areas since urban areas are the locations where nudging is found to be most necessary (Royal HaskoningDHV).
This study does not model the impact of external effects. Effect such as incoming traffic, weather conditions and time of day are not included in this study to keep focus on the main research question. The environment itself will also not model a specific city, so aspects like familiarity with the environment do not influence results.

1.4 Reading guide

Chapter 2 presents the theoretical framework on which the rest of the research is built. It talks about multiple important aspects such as, infrastructural aspects and personal characteristics influencing cyclist behaviour, methods to influence behaviour, ways that nudging has been used in the past, and ways that nudging can be used to nudge cyclist route choice in the present.
Chapter 3 discusses the methods that are used to give answer to the main research question. This includes the research design, experiment design, experiment setup, experiment procedure, data collection, data analysis and participant characteristics.
Chapter 4 discusses the results of the experiment. It talks about the results of the qualitative, descriptive, and model analysis. It also synthesises the results linking it to the literature review.
Chapter 5 concludes the report. It answers all sub-questions, gives a discussion on the methods, and gives practical and research recommendations.

2 Theoretical framework

A thorough literature review answers the first sub-question: *what factors influence route choice according to literature?* To make sure the literature review is well structured and well laid out the guidelines from (Wee B. V., 2016) are followed. Only articles from peer reviewed papers are included. The included papers are mostly from within the last 10 years, to make sure the research is up to date and still relevant. However, some older papers and books describing important concepts are also included because of their timeless influence. Papers are included from experience, compulsory papers from courses and papers recommended through expert counseling. All these papers are reviewed for the journals under which they are published. Furthermore, papers are searched using Scopus and Google scholar. To find these papers the following keywords are used:

Table 1 Search engines and truncations

Search engines	*Scopus, Google scholar, Google*
Keywords	*Cyclists, Nudging, behaviour, route choice, urban design, infrastructure, safety, Wayfinding*
Truncation	*Cyclists (AND) Nudging (AND) urban design (OR) Infrastructure* *Cyclists (AND) Behaviour (AND) urban design* *Cyclists (AND) Behaviour (AND) Nudging* *Cyclists (AND) Behaviour (AND) Safety* *Nudging (AND) Behaviour* *Nudging (AND) route choice* *Wayfinding (AND) Nudging* *Wayfinding (AND) Cyclists*

The papers found through these truncations are first filtered by title and then further filtered by reading the abstract and conclusion. The most promising papers are read more carefully and included if they are deemed useful for the research. The selected papers are all snowballed forwards and backwards to find more relevant papers. This results in a total of 68 sources.
Some information was also gathered through expert counselling. Most information they have given was also retraceable to scientific papers, but where this was not possible the paper refers to Royal HaskoningDHV

2.1 Aspects important to cyclist route choice behaviour

There are many aspects in infrastructure that influence people's route choice. Cycling and driving behaviour are very subjective matters. They can be influenced by all kinds of different factors. (Segadilha, 2014) found that factors like number of buses, traffic density and traffic speed are big factors in deciding cyclists route choice. This paragraph discusses some other important factors such as distance, safety, and emotions.
Emotions have a large influence on driving and cycling behaviour. (Roidl, 2014) found that anger and anxiety increase driving speed whilst lowering spatial awareness. Emotions can change people's behaviour in all kinds of different ways. For example, annoyed people cycle more recklessly in the rain and anxious people avoid routes with buses and trucks. (Asutay, 2019) state that sound is a big catalyst for emotions. Since emotions influence people's behaviour, sound could theoretically be used to affect their cycling behaviour.
Another important factor is perceived safety. Cyclists are vulnerable road users and should be handled in such a way. They value their own safety but do seem to overestimate their own capabilities which can cause them to make risky decisions. This way cyclists can become quite unpredictable and often break traffic rules. (Shaw, Louise, 2015) found that cyclists mostly break the rules because of self-determined poor infrastructure design. This means that redesigning infrastructure to better fit the views of cyclists can make them more compliant to the rules.
Another important reason for risky routing decisions is distance. (Law, 2014) suggest that directness is more important to route choice than safety and comfort. (Song, 2017) performed a study into the risky route choices of cyclists. A thought experiment was conducted where a cyclist had to take a small detour to get

to a traffic light to cross the street. The longer this detour became, the more people broke the rules and crossed the street without a traffic light.
Literal distance is not the most important factor. Since distance is a subjective matter, perceived distance plays an even bigger role. A study by (Nohad, 2008) reveals that cyclists do not always take the shortest path possible. (Dalton, 2015) discovered that the average bicycle trip is 27% further than the shortest option. Cyclists prefer paths with dedicated cycling infrastructure and with few interacting traffic. They also prefer paths with the least decisions to be made. Therefore, paths with few turns are felt shorter and are more popular to cyclists (Bond, 2020)P193. It is important to keep these factors in mind when designing cyclist infrastructure.

2.2 Personal characteristics influencing route choice behaviour

Different humans react differently to impulses. Human characteristics like age, gender and even the dominant writing hand can be of influence on how people react to the built environment (Bond, 2020)P99. It is crucial to know what sets people apart when influencing their route choice behaviour.
The human characteristic which is thought of most commonly is gender. Gender plays a role in wayfinding strategies, although most of these differences come through nurture rather than nature (O'Connor, 2019), (Bond, 2020)P125. Cycling safety is found somewhat more important to women (Prati, 2019). Also, female cyclists are more sensitive to lighting conditions than men. (Rupi, 2023) suggest that female cyclists tend to avoid complex road elements such as intersections without traffic lights and left turns more often than men, however, this difference diminishes with age. Women also rely more on the environment and less on spatial clues like distance when wayfinding (Bond, 2020)P123. (Schubert, 2022) found that men and women react differently to several forms of choice architecture. These studies suggest that different genders could react differently to nudges in the environment.
Age is another human characteristic which is of influence on route choice behaviour. (Stinson, 2003) state that comfort and traffic conditions are the most important factors to older people, whereas distance is found to be the most important amongst younger people.
Another factor which has been proven to influence wayfinding is familiarity. (Kubat, 2020) found that people who are less familiar in an environment are much easier to influence with environmental cues, since less familiar users tend to look more at contextual cues to aid in their wayfinding. These people also tend to make less turns and gravitate more to well identifiable roads (Chen, 2020).
There are also multiple factors that can influence the tendency of people to move either right or left.
(Beek, 2024) found that people have a right-handed tendency. When no nudging is put in place 53% of all participants turn right. The study also states that this tendency dissipates whenever nudging is applied. It is speculated that this tendency can come from people driving on the right side of the road or people being right-handed. (Bond, 2020)P179 state that eye dominance has an impact on route choice. They found people with a dominant right eye are more likely to turn right when their straight path is obstructed, for example when they face a cliff in a desert.
Other than the characteristics listed here a plethora of other demographical aspects have been included in previous studies. Factors like employment, house ownership and physical health have all been researched, but no significant correlations have been found (Dalton, 2015).

2.3 Methods to influence route choice behaviour

People's choices can be influenced in three different ways: by incentivizing favoured choices, by education, and by limiting the choice space (Hansen, 2016). In psychology this last method is often called paternalism (Camebridge, 2024). These three possibilities of choice diversion are explained further in this paragraph.
Incentivizing favourable choices is the most straight forward way of changing people's behaviour. As already discussed in section 2.1, people tend to use the fastest route. If the favourable route is made the fastest one, more people will take it. Monetary incentives can also be used. (Bie, 2009) conclude that monetary incentives are successful in changing route choice behaviour for car traffic. However, it has not been tested

for bikes. Another common way of incentivizing favourable route choices is by discouraging unfavourable ones. Laws and regulations with patrolling officers and fines are what drives safety to be a priority amongst motorists (Lyndel Bates et Al., 2012). It is not always possible to make the preferred road quicker, especially in a city centre. Monetary incentives and more law enforcement are very expensive. Therefore, other methods are also used.

Education is another method to change choice behaviour. A driver cannot make the right decision if it does not know what it is. A common use of this is traffic signs. Each traffic sign informs the road user of the favourable or required course of action. A more involved way of informing road users is by using real-time route diversion (Spiliopoulou, 2018). This system detects where traffic jams are bound to occur and diverts traffic to less congested roads. Almost every navigation system uses such systems nowadays. But for cyclists informing does not always prove useful. (Shaw, Louise, 2015), (SWOV, 2023) state that cyclists often break traffic rules, even when they are correctly informed. This means that informing works less well for cyclists than it does for cars.

A third way of changing behaviour is by limiting people's choices. In psychology this is often called paternalism. *"Paternalism is the interference of a state or an individual with another person, against their will, and defended or motivated by a claim that the person interfered with will be better off or protected from harm."* (Stanford, 2020). Paternalism is all about limiting the choices of individuals to improve their wellbeing. A paternalist would modify a car to make driving over the speed limit literally impossible. There are two main forms of paternalism. Hard paternalism and libertarian paternalism.

Hard paternalism actively limits people's choices. For example, by implementing intelligent speed adaptation systems to make driving over the speed limit impossible. (Nyholm, 2016) State that using such an Intelligent Speed Adaptation system (ISA) is justifiable due to the Harm principle. However, it also states the main problem of hard paternalism. *"It erodes the moral agency and responsibility of drivers"* (Nyholm, 2016). Hard paternalism does not only raise the ethical question of safety versus freedom. It can even result in malpractice since people feel offended. Public opinion is often stacked against limiting choice freedom (Nyholm, 2016).

Libertarian paternalism is often called nudging. A libertarian form of ISA would make it harder for the driver to drive over the speed limit. Drivers would be required to physically put in extra force to drive over the speed limit. This way the driver is nudged in the right direction without fully taking away their decision. (Sunstein, 2003) argue that people are very poor decision makers and should be nudged in making the right decisions. (Hansen, 2016) Clarifies that a nudge is an intervention that changes people's behaviour without limiting any choices nor giving any economic incentives. The views on the use of nudging are controversial (Elvebakk, 2015). Some people deem it to be a form of covert paternalism. Nudging can easily be used to influence choices in a way which is only favourable for the nudging entity and sometimes even harmful to the public. Current practices in the marketing branch are the best example of this (Singh, 2019). Critics advice governments to use these methods sparingly and only when their effects are well documented (Elvebakk, 2015).

2.4 Nudging in practice

Nudging has been used sparingly in the transportation sector. In practice, nudging is predominantly used to make people choose healthier food options. In a cafeteria, for example, the deserts can be laid out behind the fruits (Thaler, 2008). This way people are nudged to take the fruit instead of the less healthy deserts. (Arno, 2016) found that nudging people by changes in environment, marketing, and availability of food options result in an average increase of 15,3% in healthier food consumption. Nudging is used in public spaces to control crowds (Bandsma, 2021).

In Gothenburg Sweden transverse stripes have been placed on the ground to lower cyclists' speeds in uncontrolled intersections (Kovaceva, Jordanka, 2022). They conclude that nudging slightly decreases the speed of leisure travellers, but not for commuters. They also conclude that the effect is hard to measure since effects like wind have a much higher impact on approach speed. (Charlton, 2003) conducted an experiment in which they decrease visibility to lower drivers approach speeds on an urban intersection. They

conclude that lowering visibility can result in a 30% decrease in both average and 80th percentile approach speeds, whilst keeping perceived safety on the same level.
Colour in infrastructure design is also an effective way of nudging. A study in Oslo observes that colouring cycle paths does not change the willingness of people to cycle, but that it does change the route choice of cyclists as well as their salience (Fyhri, 2021). It also nudges motorists to stay clear of the cycle path and lowers the tendency of motorists to park on the cycle paths. (Chen, Jun, 2023) found that colouring sidewalks stimulate perceptual salience and individuals' moods, thereby increasing travellers' desire for walking.
On the topic of nudging route choice (Fuest, 2023) have done a study into how cartographic symbols influence route choice behaviour. They conclude that invoking emotions in people through map design can significantly influence route choice behaviour.
Lighting has also been used to nudge route choice behaviour in the past. (Buikstra, 2021) state that lighting conditions do in fact influence route choice behaviour. However, the current research could not conclude in what way this is best applied.

2.5 Exploring intervention methods

Infrastructure has not been used systematically to influence cyclist route choice. However, there are many concepts in literature that can prove to be effective in achieving this. This paragraph provides a comprehensive list of possible intervention methods, along with a synthesis into the theories on which these are based. This way this paragraph answers the third sub-question: *which infrastructural interventions can be taken to nudge cyclist route choice?*

2.5.1 Obstruction

Obstruction is the first possible method using nudging. It involves blocking the sight to one of the possible exits to make it a less favourable choice. Restricting vision is a form of nudging which has already been used for other purposes. (Charlton, 2003) show that lowering visibility is an effective way of lowering drivers' approach speed. Because people don't exactly know what is coming, they reduce their speed to make sure it is safe. This does not only influence driving speed. (Gath-Morad, 2021) show that pedestrians do the same when wayfinding. If the desired end location is in sight, they directly lock on and go there, but when the location Is not directly visible, they tend to wander before deciding. This behavior can be harnessed as a form of screening (Cullen, 1961). By making the road to the right pop out more a decision is enforced.

2.5.2 Hierarchy

The second form of nudging is by changing directness. (Dill, 2008) found that cyclists do not always take the shortest route. In a lot of situations, they take the route that feels the fastest. Most of the time because they must make less decisions on these routes. The process of making routes more enticing like this is often called hierarchy (Royal HaskoningDHV). In practice this can be used by physically making one road less work to travel by. With physical bumps and barriers, a physical hierarchy is created and cyclists are guided in the right direction. This hierarchical structure can also be implied less intrusively. By suggesting the right course of action with colour or road markings a path is made. (Royal HaskoningDHV) state that people often tend to follow paths, even if these paths are just suggestions. (Bond, 2020) P51 reveal that animals are biologically bound to adhere to this trait. (Lynch, 1959) also state the importance of boundaries in wayfinding procedure. Both hierarchy methods are used by (Royal HaskoningDHV) already or are now in the application process.

2.5.3 Attractiveness, deflection and herding

The third possible intervention method combines three psychological concepts: The effect of aesthetics, deflection, and herding.

Aesthetics are very important for people's wayfinding. (Kaplan, 1987) state that aesthetics change people's mood, sense of place and even their willingness to go down certain roads. There are numerous ways of making a place more aesthetically pleasing; by adding street art for example.
Deflection is a concept from urban design. It involves hiding information from a person to entice them to look further. If a building is placed in such a way that it seems to continue further than what is visible it entices people to go there and check it out (Cullen, 1961). This concept has not been used for nudging before, but this can be experimented upon.
The final way that street art can be used to nudge is by using herding behaviour. (Thaler, 2008) suggest that people's behavior can strongly be influenced by other people. Phenomena like obesity rate and college performance strongly depend on the actions of those around you. Herding behavior is often seen in the movement of animals, where animals like sheep and fish always try to remain in the group.
(Haghani, 2019) found that people in evacuation scenarios do the exact opposite by actively moving away from the crowds. This is due to people wanting to evade crowds (Li, 2019). This form of choice manipulation has been used in environmental studies to great success (Wee S.-C. , 2021). For example, placing footsteps on the ground leading towards a trashcan, greatly decreases the amount of street littering.

2.5.4 Sign placement

The next intervention method is sign placement. The presence of these signs can do more than merely giving information. A sign meant for pedestrians could also have effect on cyclists. The mere presence of an arrow to the right could entice them to go that way. Furthermore, the location of these signs could also have influence on the route choice of cyclists. (Royal HaskoningDHV) state that the location of signage is important to their effect. These signs should be placed on key decision locations to have the most effect.

2.5.5 Openness

Another method of nudging which is grounded in psychology is openness. People tend to want to move to open spaces (Royal HaskoningDHV). This can be used in two different ways.
First, an area can be made less open. By restricting the openness with either a tunnel or just making a street narrower an imaginary wall is created (Cullen, 1961). This disincentivises people from going down this route.
The second way is by making space more open. Squares can be attractive for people, especially if certain activities are committed there. It can play on their sense of place (Žlender, 2020). A square can however also deter cyclists since the effect of possession can make the space feel as a pedestrian only zone.

2.5.6 Anchor points

People often use locators during the wayfinding process. These are often churches or other landmarks (Lynch, 1959). People use global landmarks like towers to navigate and orient themselves (Yesiltepe, 2021). Other than being a key factor in orienting people, landmarks like towers can often become the focal point of an area (Cullen, 1961). These focal points often drag people in, therefore changing their wayfinding behavior. This could be used in our favor, by placing artificial towers and landmarks in key locations people could be nudged in the desired direction.

2.5.7 Light

Another effective way of nudging people's behaviour is by using light. (Hidayetoglu, 2012) found that roads with bright lights are perceived more positively. This positive reaction does not only raise the individual's wellbeing, it also actively increases orientation preferences. They say this effect is stronger on women. (Beek, 2024) have done research into the effect light brightness and colour has on pedestrian wayfinding. They find that people actively move towards areas with brighter light. It remains a question if this effect also works on cyclists.

2.5.8 Colour

Another intervention method using nudging is making use of colour. One possible way of using colour is by painting the sides of buildings specific colours. (Hidayetoglu, 2012) says that people tend to walk to warmer colours, whereas (Beek, 2024) suggests that people tend to move towards green lights and away from red.

2.5.9 Sound

The final possible method explored in this research is sound. (Asutay, 2019) state that sound is a big catalyst for emotion. Since emotion is an important factor on cycling behaviour sound could be used to nudge wayfinding (Roidl, 2014). (Freriks, 2015) have tried to use music in order to nudge people into making healthy food purchases, but to no avail.

2.5.10 Summary

To summarise, nine different nudging methods have been found rooted in psychological theory. These methods include obstruction, hierarchy, herding, sign placement, openness, anchor points, colour, light, and sound. In theory these methods all have the capacity to change cyclist route choice. The most promising methods are selected in section 3.3.2 to be experimented upon. It is important to note that the methods that are not researched in this study are still worth researching themselves.

3 Methodology

This chapter describes the methodology used to answer the main research question: *how can infrastructure be used to nudge cyclists to make specific route choice decisions?* This methodology also answers the second sub-question: *how can the effects of nudging techniques effectively and efficiently be measured?* Section 3.1 gives an overview of the whole research process. Section 3.2 describes how expert counselling will be used in this research. Section 3.3 discusses the experiment design decisions. Section 3.4 presents the physical experiment setup. Section 3.5 discusses the survey generation for the stated choice experiment. Section 3.6 gives and overview of the experimental procedure. Section 3.7 discusses the data that is collected. Section 3.8 goes into the data analysis. Finally, section 3.9 presents the characteristics of the participants.

3.1 Research design

The aim of this research is to explore the ways infrastructure can improve cyclist route choice behaviour with nudging. To achieve this aim five sub-questions are set up. An overview of all sub-questions and their corresponding methods can be found in Table 2.

Table 2 Sub questions and methods

How can infrastructure be used to nudge cyclists to make specific route choice decisions?	
Sub questions	***Method***
What factors influence route choice according to literature?	*Literature review*
How can the effects of nudging techniques effectively and efficiently be measured?	*Literature review, expert counselling*
Which infrastructural interventions can be taken to nudge cyclist route choice?	*Literature review, expert counselling*
What is the impact of infrastructural interventions on cyclist route choice?	*Stated choice experiment, Data analysis*
What participant characteristics influence the effect of nudging on cyclist route choice?	*Stated choice experiment, Data analysis*

The following flowchart describes the process of acquiring answers to the five sub-questions.

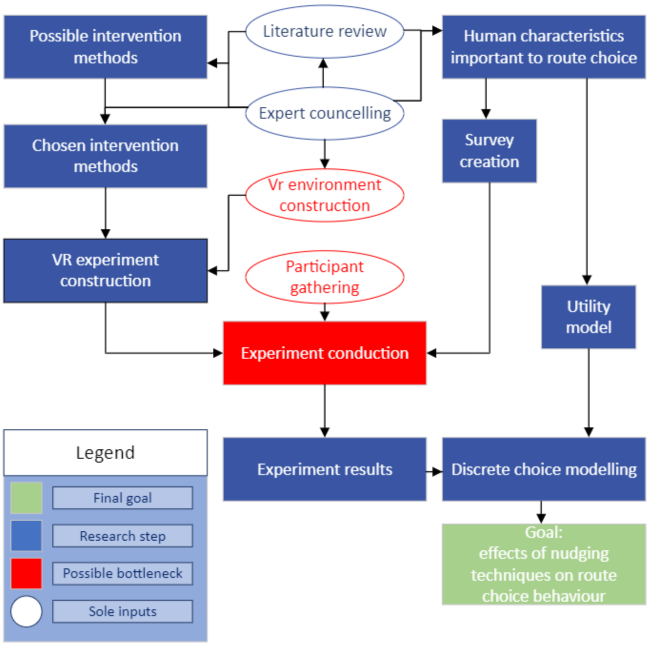

Figure 4 Flowchart research process

The research process consists of two main paths, which converge in the final modelling step. First, literature reviews and expert counselling will be used to acquire sufficient knowledge into the subject. With this knowledge a set of possible intervention methods is made. A VR environment is constructed, and these intervention methods are implemented within this environment. At the same time human aspects important to route choice behaviour are identified. With these aspects a utility function is set up, as well as a survey to be held before the VR experiment. These results are then used together with the utility function in a discrete choice model. This way the effects on route choice of every intervention method can be described. The steps which are marked red are parts that could become bottlenecks. Participant gathering and experiment conduction are deemed possible bottlenecks since there are a lot of people who need to cooperate for these steps to be fulfilled. Furthermore, consequent steps cannot be taken until these steps are finished. To combat this, a lot of time is planned for both steps. Around double the time expected to be necessary. VR environment construction is expected to be a possible bottleneck since this framework is new to the author. A lot of precautions are already taken to combat this, but if the environment cannot properly be constructed due to any reason, the experiment can be changed into a photo survey enforced stated choice experiment (Duives, 2015).

3.2 Expert counselling

Since research into the effect of nudging on route choice behaviour is lacking, this research is also based upon expert counselling; specifically, theory-generating expert interview (Döringer, 2021). This form of expert counselling is good for generating new theoretical insights, where current theory is lacking. A diverse group of experts with expertise in a wide range of fields are interviewed, focussing on subjects like nudging methods, human characteristics that influence route choice and proper experiment setup. These experts mainly consist of employees of Royal HaskoningDHV. The interviews are used to gain general insight needed to perform further research.

Table 3 Expert meetings

Profession	***Subject***
Integral advisor	*Uses of nudging in practice (Groningen)*
Integral advisor	*Uses of nudging in practice (Arnhem)*
Urban planner	*Natural wayfinding and signage*
Traffic psychologist	*Important factors to cycling behaviour*
Traffic psychologist	*Important people and sources*
Integral advisor	*Uses of nudging in practice (Bennekom)*
TU-Delft Researcher	*The use of VR to model behaviour*
Traffic psychologist	*General discussion about subject*
Royal HaskoningDHV Team	*Defining the setup of the experiment. The context, the methods, concepts and the reason for the exclusion of other methods*
Urban planner	*Discussing experiment design*
Behaviour team	*Presenting experiment design*
VR zone team	*General VR experiment notions*

In Table 3 the experts interviewed for this researched are listed with their profession and the expertise for which they were interviewed. The integral advisors showed what is already done in practice, whereas the traffic psychologists gave useful papers and books to strengthen the theoretical framework. The Royal HaskoningDHV team and behaviour team were important in selecting the most promising intervention methods and to decide on the method variants. The VR zone team and TU Delft researcher gave useful tips and literature on constructing an effective VR experiment. Most information they have given was also retraceable to scientific papers, but where this was not possible the paper refers to Royal HaskoningDHV or the VR Zone Team.

3.3 Experiment design

This experiment uses Virtual Reality (VR) experiments. This paragraph discusses why this method is chosen. Then, it goes the design of the intervention methods, the design of the virtual environment, and the design of the experiment.

3.3.1 Explanation for the use of VR

There are multiple ways of researching cycling behaviour. (Feng Y. , Data collection methods for studying pedestrian behaviour: A systematic review, 2021) present the pros and cons of the three most used research methods: field observations, surveys, and controlled experiments.

Field observations involve tracking human decisions in real life scenarios. This method is very useful for its realism, since it captures human decision making in their natural habitat. It is however not chosen due to its lacking controllability (Feng Y. , Data collection methods for studying pedestrian behaviour: A systematic review, 2021). Previous experiments have concluded that measuring the effects of nudging on behaviour is very hard in a real-world scenario (Kovaceva, Jordanka, 2022). Factors like wind have a very big effect compared to nudging. The methods that are to be researched are all experimental in nature. Therefore, it is important to strictly control the environment, to make sure that the intervention methods are the only factors that are changed in between versions.

Surveys are stated choice experiments in which a large group of respondents fill in a questionnaire. These experiments can be controlled very well. They also have the added benefit of being able to collect all kinds of participant characteristics. However, the answers that are given are not always representative (Feng Y. , Data collection methods for studying pedestrian behaviour: A systematic review, 2021). The choices made in a survey can differ from the choices that people would make in real life. This is especially the case for subconscious decisions. Surveys are not favourable since nudging is expected to mainly work subconsciously.

Controlled experiments are a trade-off between field observations and surveys. It keeps the environment controllable whilst keeping the choices made as representative as possible. It can however be rather costly. Especially in this exploratory research a lot of different methods are tested. These all must be built, making it expensive.

Therefore, a VR experiment with a bicycle simulator is chosen. A VR experiment is a controlled experiment that comes with the benefit of being more controllable and less costly. The choices made are less representative than a normal controlled experiment (Feng Y. , Data collection methods for studying pedestrian behaviour: A systematic review, 2021). However, a VR experiment is proven to be more representative than surveys due to the increased immersion (Mokas, 2021). The experiment should be as close to reality as possible for the most representative results.

It is important to note that the behaviour found in a VR experiment is not fully representative. This research will merely be an exploration of the different intervention methods. Promising interventions should be tested in a physical experiment to verify their validity.

3.3.2 Defining intervention methods

Paragraph 2.5 presents a list of possible intervention methods. Together with several employees of Royal HaskoningDHV the most promising methods are selected to be researched. In the VR experiment a total of 11 intersections can be tested, since the risk of choice exhaustion becomes too high with more choices (VR Zone team). Therefore, it is important to only research what is most necessary and promising. This paragraph presents all intervention methods and why some were left out.

It is important to note that the exclusion of certain intervention methods does not mean that they are not worth researching. In some cases, the opposite is even the case. Several intervention methods are left out since they are expected to need full research on their own. This selection has mostly been made based on practicality to be used soon. Therefore, the chosen methods are relatively small interventions.

Table 4 Overview of all possible intervention methods

Intervention	***Was it chosen?***
Obstruction	*Chosen*
Hierarchy	*Chosen*
Herding	*Chosen*
Signage	*Not chosen*
Openness	*Not chosen*
Anchor points	*Not chosen*
Light	*Not chosen*
Colour	*Not chosen*
Sound	*Not chosen*

Three intervention methods are tested with three variants each. This is done since these three interventions stood out the most and it is important to test each method multiple times, to make sure it has effect. Consequently, it can also be investigated whether different variants of the same method work differently. The three variants of each intervention method are decided upon together with Royal HaskoningDHV. First the six methods that are not chosen are explained and then, the three chosen intervention methods are discussed in further detail.

3.3.2.1 Non utilized intervention methods

There are six method that are not explored. The reason for their exclusion is explained in this paragraph.

Signage
The intervention method signage involves looking at tactical sign placement. It is not chosen since it falls more into the field of signage than the field of nudging. Context is very important to the effect of signage. This context can better be explored in research solely based on signage. Furthermore, (Royal HaskoningDHV) found in previous research that signs can be hard to read in VR due to the VR resolution. Therefore, signage is not a good fit for this research.

Openness
The effect of openness is not explored in this thesis. This method is left out since applying it would be too big of an expense (Royal HaskoningDHV). Making tunnels or new squares are very large structural interventions.

Anchor points
Anchor points involves placing towers in specific locations to attract cyclists. Once again intervention is very expensive to implement. (Royal HaskoningDHV) also state that the use of landmarks is very much context related. People only use a church as an anchor point if they know this leads them to the right place. Constructing new arbitrary anchor points would therefore probably not work. Therefore, it is found to be more promising to investigate other methods.

Light, colour and sound
Nudging methods using light colour and sound is not explored in this thesis, all for the same reason. These three methods have a lot of different ways of being implemented. They all merit their own research. Including them in this study would not do them justice.

3.3.2.2 Obstruction

The first chosen intervention method is obstruction. By obstructing vision from an intersection cyclist could be nudged the other way. This method is very promising. It is an intervention method which does not require too much infrastructural redesign. Since municipalities are already obliged to increase the amount of greenery on the roads this could fit in with that vision.
Three different objects are chosen to obstruct the view in the experiments. All three are objects that are often seen in the city image. A tree, a hedge and an advertisement sign (add-sign).

Figure 5 Tree (left), bush (middle), add-sign (right)

The tree is chosen since it is found to be the most promising. If placing a tree is found to be an effective nudge it will be a popular choice for municipalities, since municipalities are already obliged to add more trees in the city center.
The bush is chosen since it blocks the bottom side of the view instead of the top side of the view. Since the hedge blocks the view of the road more it is hypothesized to have a larger effect than the tree.
The add-sign is thought to have the weakest effect, since it blocks only a small part of the view. Still, it is added, since implementing this by far takes the least effort. If it is successful in nudging cyclists, it could be used immediately.

3.3.2.3 Hierarchy

Hierarchy involves introducing a hierarchical structure in the roads. By creating a physical barrier in between two roads, with colour, stripes or traffic bumps one road is formulated as being the main road compared to the other.
This method is found promising since it requires little infrastructural intervention. This method is already used very often, but no empirical research has been done into the effects of it. Municipalities are more often asking for empirical research, so this research could help validate the effectiveness of this method.The three chosen variants are: colouring one road part, adding a white diversion curve, and adding truncations.

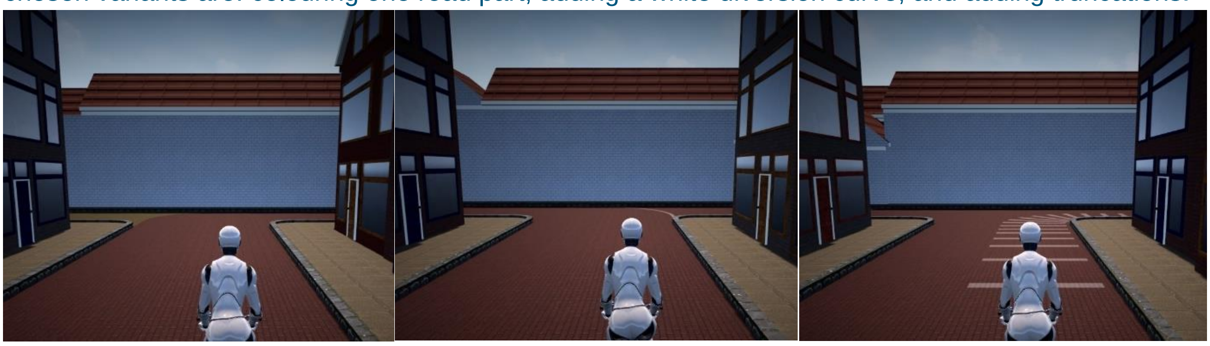

Figure 6 Road colour (left), white curve (middle), truncation (right)

These three methods are chosen because they have an increasing amount of guidance. This way it can be derived whether the level of guidance is important to the nudging strength.
Hierarchy with a physical traffic bump is notably missing from this list. This method is excluded since it is already in use so much (Royal HaskoningDHV). They can verify its effectivity by looking at their previous projects. For this study, less intrusive methods are researched.

3.3.2.4 Herding

Herding involves introducing imagery of creatures or objects moving in a certain direction. Due to herding behaviour people are coerced into doing the same. This method will be applied with street art. This method not only uses the effect of herding, but also the effect of aesthetics and deflection.
This method is the most experimental of the three methods. This method promising since herding is already used a lot in urban environments for other goals and is documented to work well there. Furthermore, adding art to an intersection is something Dutch municipalities would be eager to agree to (Royal HaskoningDHV). It is important to note that herding does not have to be done with street art but can also be done with statues or other pieces of art. Street art is merely chosen since it was easy to implement in the experiment environment. The three nudging methods are: a piece of art of a cyclist, a fish, and a wave.

Figure 7 Bike (left), fish (middle), wave (right)

In the past, herding has only been applied with drawings of human like figures. These three variants are chosen to explore the effect of abstraction on herding strength. Is it possible to influence people with any kind of drawing or do the drawings have to be of humans?

3.3.3 Design of the virtual environment

This paragraph and the next discuss the design of the VR experiment. Factors like road design, building design, control measures and equipment are important to the feel of the experiment. The are explained in this paragraph. The full design process can be found in the appendix.
The experiment environment is made in Unreal Engine 5.1. This engine is chosen for two reasons. First, it couples very well with VR. It has a lot of systems which make integrating VR in the environment effortless. Second, it is quite easy to learn. Compared to engines like Unity and coding it yourself, Unreal Engine is a very easy method of modelling an environment with a visual scripting language which makes integrating functionality quite easy.
Blender 3.6 will be used to make models as needed. To accomplish the aim of this research it is important to convey a realistic Dutch street to the participants. To accomplish this some custom models must be made since they are not publicly available. Blender is used since it is open source. Maya is thought to be more suitable for these kinds of models but due to licensing issues it is not used.
It is important to make sure that the environment makes the participants feel like they are in a Dutch neighbourhood, since it is expected that participant immersion is important to the representativeness of their results (Bogacz, 2020). However, it should not contain too much detail to reduce the number of factors

influencing cyclist route choice. The environment is modelled after a Dutch neighbourhood just outside of the city center. Since this is the environment this form of nudging to be the most useful. The environment looks like this:

Figure 8 Street appearance

The width of the road is 5,8 meters. This is the required width for a two-way car/bike shared street as registered by the CROW. The sidewalk is 2,4 meters wide on both sides. The CROW suggests 2 meters, but at some points trees will be placed in the environment and some houses will reach out a bit further on the sidewalk. The extra 0,4 meters have been chosen to accommodate for this.
The buildings are modeled in blender to resemble buildings in a typical Dutch neighbourhood as much as possible, whilst still being simplistic. The buildings are as simplistic as possible for two reasons. The first reason is to reduce processing power and environment building effort. Since the project is made by only one person this must remain as simple as possible whilst still conveying as much information as possible.
The second reason is to avoid reaching an uncanny valley. Whenever a certain level of fidelity is reached it enters uncanny valley. In this area every small detail which is wrong is noticed much more vibrantly by participants, therefore making the environment seem less realistic (Mathur, 2016).
At every turn the Field Of View (FOV) changes from 96 degrees to 60 by introducing a vignette. (Kim, 2018) conclude that this is the best way to reduce the risk of motion sickness whilst keeping the level of immersion as high as possible.

3.3.4 Design of the experiment

The experiment is set up in a specific way. The participant is told to go straight; however, they are put through 11 intersections where they must go left or right. The experiment starts with the base scenario and ends with the base scenario. This is done to snuff out any directional biases of the participants and to account for the effect of choice exhaustion (VR Zone team). This means that there is room left for 9 variants. The experiment could be made larger but (VR zone team) state that choice exhaustion becomes apparent after around 11 to 16 choices in an experiment of this notion, so a value of 11 has been chosen to be safe.
The experiment models the effect of the nine nudging variants as discussed in section 3.3.2. No interaction effects are tested, since this would make the experiment very large.

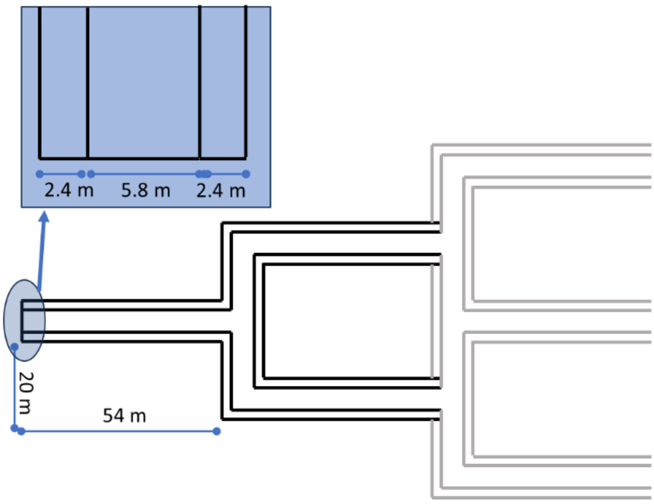

Figure 9 Road layout

Figure 9 shows the road setup that is used for the experiment. Every time the participant chooses a direction, more road is generated in only that direction. This way every participant gets the same order of intervention methods, no matter what direction they choose. Each turn is followed by a turn back, so people keep going straight. This has been done to reduce bias. If the participant would not be turned back it would feel like the participant is cycling in circles and they would correct for this to keep going straight.
Still this method could induce some bias. The participant does not return to the exact width that they were when deciding. This would cause them to veer to one side when choosing the same direction multiple times. Every intersection veers 20 meters so in total they would veer of 220 meters if they always choose the same direction.

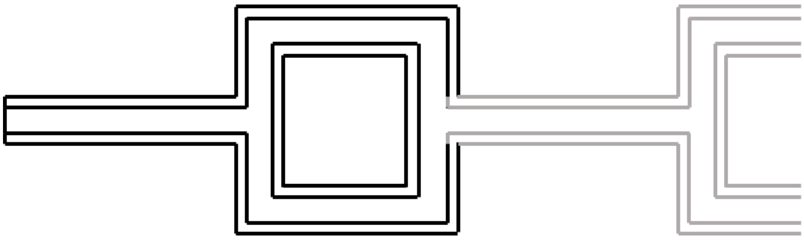

Figure 10 Non-utilised road layout

The design presented in Figure 10 would eliminate veering completely; however, it is not chosen since it would introduce twice as many turns, therefore increasing the risk of motion sickness. To reduce the effect of the veering bias the participant is told to go to the river. Since a river is a very wide target, veering off is less impactful and is therefore assumed to have less of an impact on choices. However, in the questionnaire people can say whether this veering influenced their behavior.
There are two versions of the experiment. They are both the same however, in one version all intervention methods are mirrored to accommodate for directional bias. In both versions it is made sure that the nudges nudge people in both directions equally many times, to reduce the directional bias as much as possible. This mirroring is done equally over all three intervention methods and in such a way that the nudged directions don't follow an obvious pattern.

Table 5 Nudging methods and direction

Intersection	Intervention method	Direction	Direction (flipped)
1	No intervention	None	None
2	Bush	Right	Left
3	Coloured road	Right	Left
4	Bike	Left	Right
5	Curve	Left	Right
6	Tree	Left	Right
7	Wave	Right	Left
8	Add sign	Left	Right
9	Fish	Right	Left
10	Truncation	Right	Left
11	No intervention	None	None

3.4 Experiment setup

The participants are immersed in the virtual environment with an HTC Vive. The system consists of a Head Mounted Display (HMD) with one base station and two hand controllers. The two controllers are strapped to the bike simulator used in the experiment. Other HMD's are considered but not chosen since the HTC Vive controllers fit the best on the bicycle simulator.
The VR environment run on Unreal engine 5.1 and Steam VR. The game engine and VR software ran on a Intel I9-12900hk CPU and a NVIDIA Geforce RTX3080TI graphics card.

Figure 11 Experiment setup

The bicycle setup is controlled using a Raspberry Pie and the Tackx system. The Tackx system is often used for cycling training for sports cyclists since it can realistically introduce road drag. It is however not very quick. It has a delay of 3 seconds between input and output. For sports cycling this is no problem, but for realistic experiments it can pose trouble. Therefore, the setup is modified with a Raspberry Pie. The Raspberry Pie is programmed by Dr. Yan Feng and XR Zone at Delft University of Technology with a plugin to monitor the speed of the bicycle. This system has a delay of 0.01 seconds to give a realistic real time representation.

The participants can turn the bike in VR by pressing buttons on the controllers. These controllers are strapped to the handlebars with rubber bands and tape, for easy removal. A basic table fan blew wind in the face of participants to reduce motion sickness and increase immersion. As (Chang, 2020) state, an effective measure of reducing motion sickness is by creating multisensory input.

3.5 Questionnaire generation

After the VR experiment, every respondent is handed a short questionnaire. It is important to make sure that this questionnaire does not become too long, since decision fatigue is to be avoided (KATHLEEN D. VOHS, 2005).

As presented in chapter 2.2 there are a lot of demographical factors that are of influence of cycle behaviour. To link the choices to demographical factors every participant must fill in a questionnaire. The full questionnaire can be found in A3: Survey questions however, some notable decisions are discussed in this chapter.

The questions asked in this questionnaire are all derived from the factors that were deemed important in chapter 2.2 with some notable inclusions. Three extra questions are added to the questionnaire that are not directly supported by literature. These questions are about awareness of being nudged, height and veering bias.

(Thaler, 2008) state that nudging still works if the person knows that they are being nudged. In this experiment this is tested. The experiment is made to be as seamless as possible, but due to the nature of the experiment there is a large chance that people figure out the purpose of the experiment. A question has been added that asks participants to guess what the purpose of the experiment is. If the participant guesses this correctly it will be assumed that they are aware that they are being nudged. If many participants guess the purpose of the experiment correctly and they react differently to the nudges, the validity of the experiment should be questioned.

A question about the height of the participant is also added. People from different heights have different vantage points on the bike. This could influence their interaction with some nudging methods, such as being able to look over the bush used for nudging.

The final additional question is about veering bias. In chapter 3.3.4 it has been noted that people's decisions could be influenced by them wanting to stay centred. A question regarding this has been added, to make it possible to analyse later.

To validate the results gathered with this research it is important to validate whether people experience the environment realistically (Feng Y. , 2022). To do this two widely used questionnaires are included in the questionnaire. The Presence Questionnaire (PQ) and the System Useability Scale (SUS): The PQ evaluates the participants feeling of presence with 29 7-point scale questions (Witmer, 2005). This feeling of presence is evaluated on four specific subsections: sensory fidelity, immersion, involvement, and interface quality. The SUS represents a composite measure of the overall useability of the simulator system (Brooke, 1996).

3.6 Experiment conduction

This VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 4336). The recruitment was done in several ways. Mainly, a convenience sample was taken. These people were all asked to snowball this information by forwarding the email. People were also contacted via social media and flyers on the university campus. Most notably people, were also recruited face to face during the experiment period, without them needing to make a reservation. The experiment was kept purposefully short. This was done to avoid choice exhaustion, but also to lower barrier for people to enter the experiment.

All participants joined the experiment voluntarily. The experimental procedure consisted of three parts:
The introduction (5 minutes) , the VR experiment (10 minutes) and the post-experiment questionnaire (15 minutes).

Introduction (5 minutes)

The experimental procedure was communicated to the participants with a written statement. In this statement the possible risks of the experiment were explained. Participant needed to sign this consent form to perform the experiment. This consent form can be found in

A4: Consent form. Finally, the controls and goal of the experiment were explained verbally. It was also explained that they should not turn the bike physically.

VR experiment (10 minutes)
Participants took place on the bicycle simulator and were equipped with the VR headset. They got time to adjust settings on the VR headset to fit them optimally. They were then put in a VR test environment, which is the same as the actual experiment but without nudges present. Here they were able to familiarize themselves with the controls and get used to the sharp turns. When they indicated to be ready, they were put in the formal experiment. Odd participants were put in the normal environment and even participants were put in the flipped version. In this experiment participants were tasked to get to the other side of town by choosing what way to go on intersections. They were given no guidance except that it did not matter how they got to the other side. When they got to the exit the experiment was stopped, participants got time to rest and were then asked to participate in the post-experiment questionnaire.

Post-experiment questionnaire (15 minutes)
After the experiment participants were asked to fill in the questionnaire described in section 3.5. This questionnaire consisted of three parts: a part related to personal characteristics, a Presence Questionnaire (PQ) and a System Usability Scale questionnaire (SUS). Participants that were short on time were allowed to skip the PQ and SUS questionnaires. After the questionnaire was complete the experiment was done, and participants were rewarded with a small snack. Five participants did not complete the experiments because they got motion sick.

3.7 Data collection

Both qualitative and quantitative data is collected. The VR environment collects quantitative data. This includes participants decisions and head rotation at every frame of the experiment. Each experiment is also recorded in OBS. The questionnaire collects qualitative data. This includes participant characteristics, their feeling of presence and the usability of the VR system. Finally, notable qualitative results are also written down. Participants are asked for their reasoning behind some choices for example. This data is used for the qualitative analysis.

3.8 Data analysis

The data analysis consists of four parts: data formatting, a qualitative analysis, a descriptive analysis, and a model analysis. The data is formatted in Python in a way that is most easy to work with for the rest of the analyses, the qualitative analysis is used to find reasoning behind choices and better explain the other results. The descriptive analysis is performed in SPSS to find general notions and behaviours and to find effects that can be modelled more extensively, and the model analysis in RStudio goes more in depth on the interaction effects.

3.8.1 Data formatting

Data formatting is done to make the data fit for further analysis. This data is formatted in Python. It consists of two main parts: Removing redundant data and encoding data. The full data formatting code can be found in A5: Data formatting code.

3.8.1.1 Removing redundant data

Some collected data is not used in the final analysis, because it is irregular or not useful for the final modelling. The removed data include time that decisions were made, head movement and the OBS recordings.

The decision time data is not used since it is not consistent. Some participants pressed the button at the time they made the decision. However, most participants pressed the button at the very last possible moment, because they thought pressing the button would make them turn instead of the bike turning by itself at the intersection. This makes the decision time data inconsistent and, therefore, not useful.
The head movement and OBS recordings are not used because the data is not accurate enough. This data was planned to be used to validate if people really look at the nudging methods. Head movement is however not the same as gaze (Zeuwts, 2016). A person does not have to turn their head to look at an object. To model gaze realistically the experiment should include eye tracking instead (Zeuwts, 2016).

3.8.1.2 Encoding data

Almost all questions are answered with text answers. For the model process these answers should be encoded into numbers. Most of the data is binary data. For gender for example, no one filled in anything other than male or female. This means that this datapoint only has two options and is therefore binary. This data is dummy coded (Moutinho, 2013). Dummy coding codes qualitative data to a 0 or a 1 based on criteria posed by the analyst.
Dummy coding can also be used to encode trinary variables by using two dummy variables. For example, when people are asked what their dominant eye is they have three possible answers; left, right or both. This data is encoded with two dummy variables; DomEyeLeft and DomEyeRight. If both variables return 0 it means that the participant has no dominant eye. All data that is dummy coded is shown in the following table.

Table 6 Dummy coding of data

Variable name	***Variable discription***	***Dummy code 0***	***Dummy code 1***
Gender	*What is the participants gender?*	*Male*	*Female*
DomHand	*What is the participants dominant hand?*	*Right*	*Left*
DomEyeLeft	*Is the participants left eye dominant?*	*No*	*Yes*
DomEyeRight	*Is the participants right eye dominant?*	*No*	*Yes*
RoadSide	*What side of the road is driven on in country of origin*	*Right*	*Left*
Commonality	*Do people often ride bicycles in country of origin?*	*No*	*Yes*
Centrality	*Did the participant put in an effort to stay centered?*	*No*	*Yes*
KnowPurpose	*Did the participant guess the purpose of the experiment correctly?*	*No*	*Yes*
ChoseLeft	*Did the participant turn left?*	*No*	*Yes*
Bush, Tree, Etc.	*Every nudging method*	*Is not applied*	*Is applied*

Some other data is of ordinal nature. Data like VR experience and cycling experience are all coded between a value of 1 and 5. Data that was already cardinal is kept the same.
Furthermore, three extra variables are added, FollowNudge, NudgeLeft and NudgeRight. These variables are used to see if participants went in the direction of the nudge and in which direction the nudge was pointing.

3.8.2 Qualitative analysis

The qualitative analysis is used to get insights into reasoning of participants. This analysis form is not planned and is therefore not structured in a specific way. In general, all participants are asked about their experience. Why did they make the decisions that they made? What worked well for them and how did they feel about the environment. Together with a general feedback option in the survey this creates a basis on which explanations for participant behaviour can be based. It is important to note that since no specific structure is followed for this analysis, the answers found cannot be verified and are therefore seen as suggestions rather than actual results. Still, they help with finding reasoning behind the answers found in the other two analyses.

3.8.3 Descriptive analysis

The descriptive analysis is performed to find general patterns in the data. Using SPSS statistics interactions between variables are explored. For this a χ^2 test is performed (Singhal, 2013).

$$\chi^2 = \sum_{i=1}^{n} \frac{(0_i - E_i)^2}{E_i}$$

A χ^2 test is a statistical test that can be used when comparing two binary/nominal variables. It assumes one variable as the dependent variable. The distribution of this variable is taken as an expected value (e_i). (o_i). Presents the observed value. What distribution is seen when the second variable is in a certain state (in our experiment this will be 1 or 0). This results in a certain χ^2 value. This value together with the degrees of freedom (1 in this experiment) represent a chance that this pattern would be seen by pure chance. For this report a confidence interval of 95% ($\chi^2 = 3{,}841$) is required. This means that there is a 5% chance that the patterns seen are present by pure coincidence.
The H_0 for this experiment is that the nudging methods and characteristics have no effect on nudge compliance. If the χ^2 falls within the confidence interval the H_0 can be discarded and it can be said that the nudging method/characteristic does have an effect on nudge compliance.
For this analysis Follownudge is used as a dependent variable. This is a dummy coded variable that returns 0 is the nudge is not followed and a 1 if it is. Follownudge is chosen as the dependent variable since this is the actual choice that people make. All other variables have an influence on this choice, therefore follownudge is dependent on them. This way it can be determined if certain nudges or characteristics result in participants following the nudge more often.
ChoseLeft is also used as a dependent variable in some χ^2 tests. ChoseLeft is a dummy coded variable that returns 0 if the participant turns right and 1 if the participant turns left.. Some effects are thought to influence directional bias. These variables are compared to the dependent variable ChoseLeft.

3.8.4 Model analysis

To compare the binary dependent variable to multiple nominal variables a form of discrete choice modelling has to be used. For this analysis the simplest model form is used; Multinomial Logit (MNL) (Maalouf, 2011). MNL uses utility functions to attempt to fit a dataset as well as possible. In this process it assigns weights to all variables put in the model, which can then be used to determine what motivates the observed choices. MNL is used since it can model complex interaction effects which cannot be modelled with only descriptive analysis. In our model it is mainly used to see if directional bias and other characteristics influence the effectivity of the different interventions.
Two more sophisticated methods were considered but not used, Mixed Logit and Latent Class discrete choice modelling. Mixed Logit is a more sophisticated form of MNL that allows for including correlation between alternatives (Hensher, 2011). Since there are only two alternatives in this choice model no unwanted correlations can show up, so Mixed logit is not necessary.
Latent Class discrete choice modelling is a more sophisticated form of MNL that can account for complex forms of taste heterogeneity (Hess, 2011). This method was ultimately not used because it would require much more data. For Latent Class modelling to be used the questionnaire must be a lot larger. This larger questionnaire would discourage people from participating in the experiment. The response group itself also had to be a lot larger. Therefore, it was deemed not achievable for this study.
The MNL model is constructed in RStudio. For this MNL model a utility function must be set up. This paragraph will go into the construction of this MNL model. First, the final utility function is given and then the reasoning behind this formulation is explained.

$$U1(Left) = \quad Nl * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$$

$U2(Right) = DB + Nr * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$

$(Obstruction)Obs = \beta_{Tr} * Tree + \beta_{Bu} * Bush + \beta_{Ad} * Add$
$(Hierarchy)\ Hier = \beta_{Ro} * Road + \beta_{Cu} * Curve + \beta_{Tu} * Truncation$
$(Herding)\ Herd = \beta_{Bi} * Bike + \beta_{Fi} * Fish + \beta_{Wa} * Wave$
$(DirectionalBias)\ DB = \beta_0 + \beta_{el} * DomEyeLeft + \beta_{er} * DomEyeRight + \beta_{hr} * DomHand + \beta_{rr} * RoadSide$
$(Characteristics)\ Char = (1 + \beta_{gobs} * Characteristic)$**
**$With\ different\ \beta\ For\ the\ 3\ different\ interactions\ and\ a\ factor\ for\ each\ characteristic$

To make the utility function easier to digest, it is explained in parts. The parts are in the following order. First, the main body with the dependent variable and the overall structure. Then, the formulation of the directional bias. Next, the formulation of the nudging methods and finally the formulation of the characteristics.

Main body
This part of the function is important to the structure of the utility function.
$U1(Left) = \qquad Nl * (\dots)$
$U2(Right) = DB + Nr * (\dots)$

This utility function has ChoseLeft as a dependent dummy coded variable. ChoseLeft returns 1 if the participant turned left and 0 if they turned right. FollowNudge is not the dependent variable since there are situations in which no nudging is in place. At the start and the end of the experiment a base situation is used with no nudging in place. Since there is no nudge in place FollowNudge becomes 0 by default. If the whole dataset is estimated with FollowNudge as the dependent variable there are datapoints which convey no datapoints, since the dependent variable is 0 by default. This makes SPSS crash when estimating for the whole dataset.
This model checks whether people follow the nudge by introducing the factors NudgeLeft (Nl) and NudgeRight (Nr). These are both also dummy coded variables. The part between brackets is the same for both functions. If the nudge is to the left Nl becomes non-zero and the whole equation would look like this:

$U1(Left) = \qquad 1 * (\dots)$
$U2(Right) = DB + 0 * (\dots)$

When there is no nudging both Nl and Nr become zero and only the Directional bias (*DB*) becomes of influence making the equation look like this.

$U1(Left) = \qquad 0 * (\dots)$
$U2(Right) = DB + 0 * (\dots)$

This is in line with expectations since it is assumed that the only thing influencing cyclist decisions are the nudges and the *DB*. The *DB* has been added to the right since it is expected to point right.

Directional Bias
This part of the function is important to the directional bias.
$(DirectionalBias)\ DB = \beta_0 + \beta_{el} * DomEyeLeft + \beta_{er} * DomEyeRight + \beta_{hr} * DomHand + \beta_{rr} * RoadSide$

The *DB* is dependent on four dummy variables. Each of these variables gets a weight (β) assigned to them. The model tries to estimate values for each β to come as close to the choices as represented by the dependent variable. A β_0 is added as well since it is expected that the directional bias cannot fully be explained by the other four variables.

Nudging methods and characteristics
For explaining the formulation of the Nudging methods, the rest of the model is added.

$$U1(Left) = \quad Nl * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$$
$$U2(Right) = DB + Nr * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$$

$$(Obstruction)\ Obs = \beta_{Tr} * Tree + \beta_{Bu} * Bush + \beta_{Ad} * Add$$
$$(Hierarchy)\ Hier = \beta_{Ro} * Road + \beta_{Cu} * Curve + \beta_{Tu} * Truncation$$
$$(Herding)\ Herd = \beta_{Bi} * Bike + \beta_{Fi} * Fish + \beta_{Wa} * Wave$$
$$(Characteristics)\ Char = (1 + \beta_{gobs} * Characteristic)^{**}$$
$$^{**}With\ different\ \beta\ For\ the\ 3\ different\ interactions\ and\ a\ factor\ for\ each\ characteristic$$

The nine intervention variants are separated into the three nudging methods. Every nudging method is a dummy coded variable and has its own β. It is important to note that the effect if each intervention is assumed to be the same in both directions. This is done because modelling the effects differently in both directions led to illogical results.
Every characteristic is modelled through an interaction affect with each nudging method. It is defaulted to 1 and can become higher or lower if the dummy variable becomes 1 and the characteristic is active. For each characteristic three different β values are assumed. This is done since it is expected that different characteristics interact differently with different nudging methods. For example: it is expected that women react more intensely on herding methods and less intensely on hierarchy factors. Therefore, a different β is assumed for the three different nudging methods.
Before the MNL model is set up a descriptive analysis is performed with as a dependent variable being whether people followed the nudge or not. Usually, only characteristics that have a significant effect in the descriptive analysis are included in the MNL model, however for this experiment it is expected that some interaction effects can be contradictory to each other and therefore be more significant that the whole characteristic overall. Therefore, all interaction effects of all characteristics are individually checked.

3.9 Participants characteristics

In total 106 participants took part in the experiment. 5 participants stopped the experiment because they got motion sick and 2 participants were excluded since they solely turned left or right during the experiment, so 99 participants were deemed to have valid results.
From these participants 33 were female and 66 were male. The age varies between 18 and 70 with an average age of 31. Most participants (62%) cycle every day. Furthermore, most participants (70%) have almost never used a VR system, and quite a big portion (43%) of participants play video games often. There was no question about education level, but since most participants were either students from TUDelft or employees of Royal HaskoningDHV the average education level is assumed to be high. It is important to note that 70 of the 99 participants guessed the purpose of the experiment correctly. The participants characteristics are summarized in Table 7.

Table 7 Descriptive participant characteristics

Descriptive information	Category	Number (percentage)
Gender	Male	66 (66,67%)
	Female	33 (33,33%)
Age	<20	3 (3,03%)
	20-25	33 (33,33%)
	26-30	34 (34,34%)
	31-40	13 (13,13%)
	>40	16 (16,16%)
Cycling Frequency	Never	5 (5,05%)
	Less than once a week	6 (6,06%)
	1-2 times a week	6 (6,06%)
	3 times a week or more	20 (20,20%)
	every day	62 (62,63%)
VR Experience	Very often	3 (3,03%)
	Often	3 (3,03%)
	Neutral	23 (23,23%)
	Barely	45 (45,45%)
	Never	25 (25,25%)
Game Experience	Very often	20 (20,20%)
	Often	23 (23,23%)
	Neutral	30 (30,30%)
	Barely	25 (25,25%)
	Never	1 (1,01%)

The participants perception of the Virtual environment is evaluated with the Presence Questionnaire (PQ) and the System Usability Scale (SUS). The PQ evaluates the participants sense of presence by asking 29 questions on a 7-point Likert scale (Witmer, 2005). The average total score of the PQ is 123,49 (SD = 17,67). This indicates that the participants have quite a good sense of presence in the virtual environment. It is higher than several similar VR experiments (Deb, 2017), but lower than some others (Beek, 2024). The PQ score has been split out in the four sections in Table 8.

Table 8 PQ score sections

Section	Average score	Standard deviation
Involvement	4.48	0.80
Sensory fidelity	3.46	1.00
Immersion	5.30	0.75
Interface quality	3.67	1.02

In general, sensory fidelity and interface quality are rated the lowest. Participants had trouble with correctly adjusting the screen sharpness, so the vision was blurry for some participants, therefore interface quality scored lower. Sensory fidelity scored low since a lot of questions were about sound design. Sound scored low since it is not a focus of this research. The background sounds were often not noticed, and the sound that the bicycle simulator made was quite loud which was found to be distracting for participants.
The SUS questionnaire determines the usability of the system. It consists of 10 questions which are all answered on a Likert scale of 1 to 5. This score is then multiplied by 2,5 up to a maximum scale of 100. The average total SUS score is equal to 73,09 (SD = 6.72). This indicates that the VR environment has a good usability (Bangor, 2009). This result is slightly lower than the research by (Beek, 2024) but higher than (Feng, 2021)

4 Results

In this chapter, the results of the experiment are presented. First some qualitative results are discussed, then a descriptive analysis is performed, next the results of the discrete choice model are presented and finally, a synthesis takes place that compares the found results to literature and discusses reasoning behind these results.

4.1 Qualitative analysis

During the experiment the most notable observations and opinions of participants are written down. These are all important to further support the behaviour found in the experiments.
The fan used to generate wind during the experiment broke during 8 experiments. From these 8 experiments 4 participants got ill and stopped the experiment, whereas in 98 experiments with a fan only 1 person stopped the experiment due to motion sickness. This suggests that the fan greatly reduces motion sickness which is also supported by (Chang, 2020), however the dataset is not large enough to prove this statistically. Participants that reported minor inconvenience due to motion sickness reported that they especially got sick from the turns. The sharp turns were made to reduce motion sickness, but people reported that they got disoriented from the quick turns and this made them motion sick.
Participants react differently to some intervention methods than first expected. Some of their reasoning is important to mention for further application. There was a group of participants that avoided all streets with graffiti. Their reasoning for this was that they associated street art with a bad neighbourhood. They did not want to cycle through a bad neighbourhood so avoided all streets with graffiti. Maybe a different art piece such as a statue would have worked better for these people. There were also a couple of people that followed the street art with a wave because they associated it with water. At the start of the experiment participants were instructed to go to the river at the other end of town. With nothing to lead them, they tried to find leads wherever they could. Therefore, they thought that the wave was a sign leading them to the river.
The markings on the road are almost universally followed. There were some people that strictly went the opposite way of the nudge because they did not want to follow the rules. In future research it could be useful to include a question in the questionnaire that asks people about rule following behaviour. The differently coloured road was thought to be unpaved road by some participants. This could have influenced their behaviour.
The obstruction intervention methods looked to work the least well. The bush worked as intended but the tree and the add-sign worked differently than first theorised. A lot of participants went towards the tree instead of away from it. They did this because they felt that this was the most comfortable path, since the tree was green and provided shadow. Some participants thought that this tree would mean that the rest of the path would also contain trees.
The add-sign had a coffee advertisement on it. In hindsight this was a mistake in the experiment. People that didn’t like coffee reacted to the add sign as expected, but people that did like coffee almost all went towards the sign. Hoping to get some coffee at those locations. There were also people that went towards the coffee sign because they thought this would mean a lively part of town and wanted to be amongst them. Some other people went away from the coffee sign for the exact same reason; trying to dodge the crowds. If the add sign would have been an advertisement for something more bland such as glasses, it maybe would have worked better.

4.2 Descriptive analysis

The final dataset has 99 participants all making 11 choices, totalling in 1089 data points. Some trends in the choices made are discussed here.

In general, 544 choices (50%) are made in accordance with the nudging direction, whereas 545 choices (50%) are made against the nudging direction. It is important to note that the two situations in which no nudging was implemented are included as people going against the proposed nudge, so when only including the options in which nudging was present, 61.1% of choices were made in accordance with the proposed nudge.

4.2.1 Effect of nudging methods

This paragraph gives answer to the sub-question: *What is the impact of infrastructural interventions on cyclist route choice?.* The different nudging methods all have a different effectiveness in nudging participants. Some nudging methods are also more effective in a certain direction. For every method the H_1 hypothesis is that the method is an effective form of nudging. To test this hypothesis a χ^2 test is performed with a 95% confidence interval. First the results for the obstruction methods will be discussed, then the results for the hierarchy methods and finally, the results for the herding methods. The summary of these results can also be found in Table 9.

4.2.1.1 Obstruction

One of the three nudging methods was obstruction. This method involves limiting view of one of the two directions to nudge people in the other direction. This method has three variants. A bush, a tree and an add-sign.

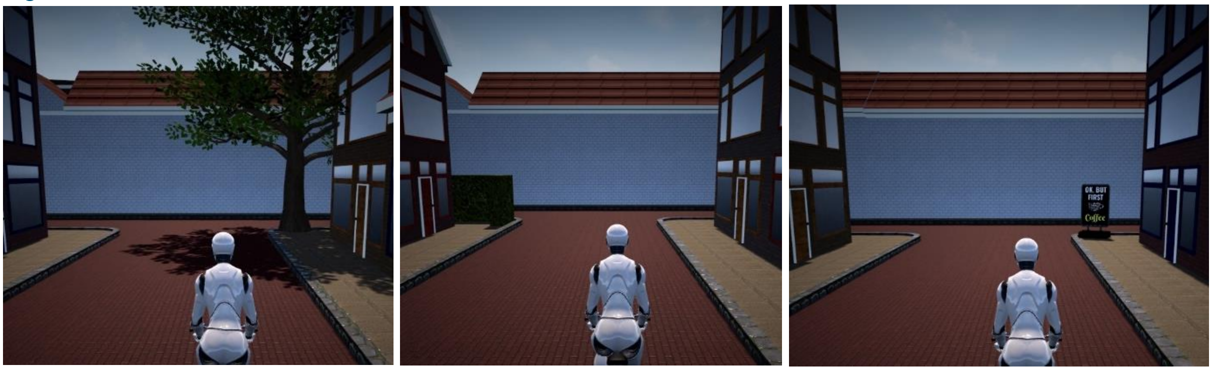

Figure 12 Tree (left), bush (middle), add-sign (right)

Bush
The first obstruction method is placing a bush. When a bush is placed on a location (left or right), 55.6% of people follows the nudge by going in the opposite direction. With a χ^2 of 1.37 This gets a p of 0.242. This means that the chance that this pattern would happen by pure coincidence is 24.2%. For this research a significance interval of 95% is required. This means that the effect of placing a bush is not significant in both directions, and therefore not an effective nudge.
The nudge is slightly stronger when performed to the right, but not significantly so.

Tree
The second obstruction method is placing a tree. When a tree is used to obstruct the view only 40.4% of people follow the nudge. More people go to the tree then away from it. With a χ^2 of 3.97 This gets a p of 0.046. This means that placing a tree is an effective way of nudging people, but in the opposite direction from first hypothesised. Qualitative analysis points out that people want to go towards the tree since it provides shadow and a green and aesthetically pleasing environment. People expect that this tree means that that direction has more greenery and thus want to go that way.
The tree nudges significantly better when it is put on the right side. When it is placed on the left it nudges 52.1% of people to the right, but when it is placed on the right side it nudges 70.6% of people to the right. If

the tree is put on the left side, it is very easily seen that there is no further greenery to come. On the right side this cannot be seen as easily.

Add-sign
The third method involves placing an add-sign. This nudge works 49.5% of the time. With a χ^2 of 0.01 This gets a *p* of 0.942. This means that this method is far from significant.
However, when the separate directions are investigated it is a different story. When it is placed on the left it nudges 68.8% of people to the right, but when it is placed on the right it nudges 31.4% of people to the left as well. This means that people always go to the right when this nudge is present, and it does not matter on which side of the road this sign is placed.
There are two explanations for this phenomenon. As explained in the qualitative analysis people were often attracted to the coffee advertisement. It could be that people can read the sign better when it is placed on the right. Therefore, they are attracted when it is on the right. When it is on the left, they cannot read the sign very well. They are then diverted by the effect of obstruction.
The other explanation is that the nudging method has no effect at all, and directional bias takes over.

4.2.1.2 Hierarchy

Hierarchy methods attempt to create a hierarchical structure in the road by placing road markings. This hierarchical structure is expected to lead people in the desired direction. For this method three variants are made. Each method has a more intense form of guidance.

Figure 13 Road colour (left), white curve (middle), truncation (right)

Road colour
The first variant involves making the desired path a different colour than the rest. 55.6% of people follow this nudge. With a χ^2 of 2.53 This gets a *p* of 0.112. This means that this intervention is not a significantly effective nudging method. This method is a lot less effective than first expected. It could be that the contrast between the two colours was not high enough to make it effective.
This nudging method is a lot more effective to the left (66.7%) then to the right (49%). There is no good explanation for this in literature.

White curve
The second method involves drawing a thin white curve on the edge of the road you want people to stay away from. 72.7% of people follow this nudge. With a χ^2 of 22.59 This gets a *p* of <0.001. This means that this method is very effective in nudging people's route choice.
It is also similarly effective in both directions.

Truncation
The third hierarchy variant involves adding transverse stripes in the direction you want people to go. This method works 74,7% of the time. This means that this is the most effective intervention method of all. With a χ^2 of 26.78 This gets a *p* of <0.001. This means that this nudging method has a significant effect.

It is also similarly effective in both directions.

4.2.1.3 Herding

The herding method involves drawing street art on the front wall with creatures and objects moving in a certain direction. According to theory people are tempted to move in the same direction as the street art is pointing. The three variants involve a drawing of a cyclist, fish, and wave. This way it can be seen if abstraction influences the effect of this nudging method.

Figure 14 Bike (left), fish (middle), wave (right)

Cyclist
The first herding method is a drawing of a bike. People follow the bike 64.6% percent of the time. With a χ^2 of 9.4 this gets a *p* of 0.002. This means that this nudging variant has a significant effect. The nudge is also similarly effective in both directions.

Fish
The second herding method is a drawing of a fish. This method works 66.7% of the time. With a χ^2 of 12.17 This gets a *p* of <0.001. This means that this nudging variant has a significant effect.
This method works better to the right (72.5%) than to the left (60.4%). The proposed reason why is explained below since it relates to the third herding method.

Wave
The third herding method is a drawing of a wave. People follow this method 67.7% of the time. With a χ^2 of 13.68 This gets a *p* of <0.001. This means that this nudging variant has a significant effect.
This method also works even better to the right (80.4%) than to the left (54.2%). This difference is so big that an explanation is in order. As visible in these results each herding method gets more skewed results than the one before. This means that the level of abstraction influences the effectiveness of the herding methods, however, in a different way than first expected.
It was expected that the effect of herding would become weaker as drawings became more abstract. A first look at these results cannot confirm this; however, a deeper look can say that this is the case. The nudging method did not only investigate the effect of herding, but also into the effect of deflection. Deflection is a phenomenon that happens because people see something interesting but cannot see it fully. People are tempted to come closer and therefore get nudged in that direction. In Figure 14 drawings on the right side were slightly cut off by the building whereas the drawings on the left were not. This means that deflection works better to the right then to the left. These results suggest that the less human a drawing becomes, the less herding influences humans and the more the effect of deflection takes over.

Table 9 Effectiveness and significance of every nudging method

Method	Effectiveness (total) (%)	Chi-Square (χ^2)	Significance (p)	Effectiveness (Right) (%)	Effectiveness (Left) (%)
Obstruction					
Bush	55.6	1.37	0.242	58.8	52.1
Tree	40.4	3.97	0.046	52.1	29.4
Add sign	49.5	0.01	0.942	68.8	31.4
Hierarchy					
Road colour	57.6	2.53	0.112	49.0	66.7
White Curve	72.7	22.59	<0.001	72.9	72.5
Truncation	74.7	26.78	<0.001	74.5	75.0
Herding					
Bike	64.6	9.40	0.002	66.7	62.7
Fish	66.7	12.17	<0.001	72.5	60.4
Wave	67.7	13.68	<0.001	80.4	54.2

4.2.2 Effect of characteristics

This paragraph gives an answer to the sub-question: *What participant characteristics influence the effect of nudging on cyclist route choice?* The participants all of course have different characteristics. Several characteristics are thought to have influence on people's tendency to follow nudges. However, as can be seen in Table 10 none of the characteristics have a significant effect on nudge compliance. It does not matter how much experience people had with VR or gaming in general. It does not matter what gender, age or height they are either. It also does not matter how often they cycle, at what age they started cycling or if cycling is a common means of transportation in their country of origin. All effects thought to influence route choice according to literature have no significant effect on the effectiveness of the proposed nudging methods.
The most important result is the effect of KnowPurpose on behaviour. 70% of people discovered the purpose of the experiment. The results show that people do not act differently when they know this. If they would have reacted differently, the experiment could not have been validated.

Table 10 Effects of characteristics on nudge compliance

Characteristic	Chi-Square (χ^2)	df	Significance (p)
Commonality	0.01	1	0.94
CycleFrequency	0.85	4	0.93
Gender	0.74	1	0.39
Height	38.25	37	0.41
Age	32.97	34	0.52
Centrality	0.47	1	0.83
GameExp	2.47	4	0.65
VRExp	1.21	4	0.88
KnowPurpose	1.55	1	0.21

4.2.3 Effect of directional bias

As discovered in previous research, people feel compelled to turn right more often (Beek, 2024). This directional bias is also observed in this experiment.
For the whole dataset 616 (56.6%) people turn right. With a one sample T-test it can be derived whether this is significantly different from a 50/50. This would mean that people are biased to go to the right. With a T-value of 28.90 this receives a *p* of <0,001. It can be stated that this difference is significant. This means that people tend to go right more often.
The directional bias becomes even stronger if no nudging is applied. If no nudging is applied people go to right 62.2% of the time. This means that directional bias becomes weaker is nudging is present. With a χ^2 of 3.62 This gets a *p* of 0.057. This is barely not significant with a confidence interval of 95% but is significant with a confidence interval of 90%. This means that it cannot be proven that directional bias becomes weaker when nudging is applied but it can be strongly suggested. A larger dataset is needed to fully prove this.
Some characteristics are thought to influence directional bias. The characteristics are hand dominance, eye dominance and on what side of the road people drive in their country of origin. It is found that all these factors have an opposite effect than expected from literature. Having a dominant right eye for example, results in people going more to the left. None of these effects are significant, however the fact that all characteristics all point the same direction by pure change is quite peculiar, and therefore merits further research.

Table 11 Effect of characteristics on directional bias

Factor of influence	*Percent turning right (%) (Base = 56.6%)*	*Chi-Square (χ^2)*	*Significance (p)*
DomEyeRight	*55.4*	*2.28*	*0.131*
DomEyeLeft	*58.7*	*1.11*	*0.293*
DomHandLeft	*56.8*	*0.01*	*0.941*
DriveOnRightSide	*56.2*	*0.68*	*0.411*

4.3 Model analysis

With the descriptive analysis performed, a MNL analysis can commence. As explained in chapter 4.2.2 every characteristic is tested for significance. Since it is expected that interaction effects are different from the overall effect of the characteristic, each characteristic is tested for interaction effects. Every characteristic has been added to the model separately, since adding them all at once would never result in significant effects. The interaction effects are calculated with the following function.

$$interaction = Nudge * (1 + \beta_{gobs} * Characteristic)$$

Only two interaction variables are significant with a confidence interval of 95% (|T| = 1,95).
The interaction between cycle frequency and obstruction has a T-value of -3,08 (*p = 0.002)*. This means that people who cycle more often are less likely to follow obstruction methods. It also means that people who are more experienced cyclists move less towards the tree. Even though most obstruction methods already have an insignificant effect, experienced cyclists are affected significantly less. Aversely, this also means that obstruction methods work better for nudging inexperienced cyclists.
The interaction between centrality (people trying to stay centred) and hierarchy (road markings) is also significant with a T-value of -3,01 (*p = 0.002)*. This means that cyclists who are trying to stay centred react less to stripes on the road. It is theorised that people who are trying to stay centred are less affected by all three nudging methods, since they are busy with staying centred. The effect is thought to be more visible since hierarchy itself has the strongest effect.

The characteristics influencing directional bias are also tested once more in the MNL model, however none of these effects are significant except for the general β_0. This means that the final utility function looks like this:

$$U1(Left) = Nl * ((Obs * (1 + \beta_{fo} * CycleFrequency)) + (Hier * (1 + \beta_{chi} * Centrality)) + (Herd))$$
$$U2(Right) = \beta_0 + Nr * ((Obs * (1 + \beta_{fo} * CycleFrequency)) + (Hier * (1 + \beta_{chi} * Centrality)) + (Herd))$$

$$(Obstruction)\ Obs = \beta_{Tr} * Tree + \beta_{Bu} * Bush + \beta_{Ad} * Add$$
$$(Hierarchy)\ Hier = \beta_{Ro} * Road + \beta_{Cu} * Curve + \beta_{Tu} * Truncation$$
$$(Herding)\ Herd = \beta_{Bi} * Bike + \beta_{Fi} * Fish + \beta_{Wa} * Wave$$

The non-significant nudging methods are included in the final model. This is done since their significance could have been changed by the other interaction variables and they themselves are important to the significance of the interaction variables.
When this model is put into Rstudio and estimated it comes to the following results:

Tabel 12 Model estimates

Variable	*Estimate*	*T-Test*	*Significance*
β_Bush	*0.68*	*1.06*	*0.153*
β_Tree	*-1.18*	*-1.49*	*0.067*
β_AddSign	*-0.25*	*-0.41*	*0.355*
β_RoadColour	*0.38*	*1.50*	*0.074*
β_Curve	*1.30*	*4.30*	*<0.001*
β_Truncation	*1.54*	*4.42*	*<0.001*
β_Bike	*0.62*	*2.94*	*0.002*
β_Fish	*0.70*	*3.24*	*<0.001*
β_Wave	*0.74*	*3.43*	*<0.001*
*β_Cyclefrequency*Obstruction*	*-0.16*	*-3.08*	*0.002*
*β_Centrality*Hierarchy*	*-0.53*	*-3.01*	*0.002*
β_0	*0.28*	*4.32*	*<0.001*

The full model has a final Log Likelihood of -698.56 (adj. $Rho^2 = 0.059$). Two notable differences can be seen in this full model.
First, the tree does not seem to have a significant effect anymore with a *p* of 0.067 it is only significant for a 90% confidence interval. This happens due to the addition of the directional bias β_0. The tree only nudges significantly to the right. Since the directional bias is also to the right a part of the behaviour can be explained by the directional bias, therefore making this nudging method less significant overall.
The opposite happens to the effect of the RoadColour. In the full model, this variable also becomes significant for a 90% confidence interval with a *p* of 0.074. This nudging method is the only one that works better to the left. Since the directional bias is pointing to the right it means that this nudging method must overpower the directional bias, therefore this method is more significant overall.

4.4 Synthesis

In this paragraph the results are discussed and compared to literature. It discusses whether the results are in line with expectation and comparative to previous studies.

4.4.1 Effectivity of nudging methods.

The effectivity of the nudging methods does not fully fall in line with expectation and literary findings.

Obstruction
It was not expected that obstruction methods would not be effective. (Gath-Morad, 2021) suggest that putting down objects to limit view would result in people going the other direction. It can be concluded that obstruction is not an effective method of nudging route choice.
The tree and add-sign have significant results, but these nudge participants in the opposite than expected. Qualitative analysis reveals that people are attracted due to these objects because they think the path ahead is more comfortable, aesthetically pleasing or other rewards (like coffee) are to be found. Aesthetics and comfort are important to wayfinding (Kaplan, 1987). The effect of these factors is much stronger than the diverting effect of obstruction. As theory suggest emotion plays a big role on cycling behaviour, so objects that elicit an emotional response could prove to be effective (Roidl, 2014).
The hedge was expected to be the most effective method of obstruction, and maybe it still is. However, since obstruction itself is not an effective nudging method and the hedge has no attracting effect, this method gets such a low significance.

Hierarchy
Hierarchy works very well. (Bond, 2020) P51 suggest that following lines is deeply rooted in people's subconscious. Therefore, it was expected to be the most effective method.
The results show that hierarchy using truncations and curves are very effective, but colouring the road is only effective for a 90% confidence interval.
The lacking effectivity of colouring the road is curious. It is a method which is used a very often by Royal HaskoningDHV and engineering firms alike, so discovering that it is only effective on a 90% confidence interval is something which is both unwanted and unexpected.
It could be that that the contrast between the two road segments was not enough to make it distinct. It is expected however, that even with a higher contrast, road colour will not be as effective as the other two variants of hierarchy.

Herding
The herding method does very well. It is based on the theory of aesthetics (Kaplan, 1987), deflection (Cullen, 1961) and herding (Thaler, 2008), but it is quite an experimental application.
The results show that all three herding variants are significantly effective. When looking at the results it can be theorised that the effect of herding becomes weaker when drawings become more abstract. In previous applications of herding, the imagery used was always human in nature (Wee S.-C. , 2021). This research is the first to suggest that more abstract drawings have less of a herding effect on humans.

4.4.2 Influence of human characteristics

Theory suggests that gender and age play a role in wayfinding behaviour. Women use visual cues more when wayfinding whereas men make more use of distance and logics (Bond, 2020). This would mean that women would react more to the herding methods and men would react more to the hierarchy methods. The results show that gender has no influence.
Older people take safety into account more than younger people (Stinson, 2003). This would mean that older people react more strongly to obstruction methods. This, however, is also not seen in the results. (Thaler, 2008) suggest that nudging works equally well if people are aware of being nudged. The results support this theory and show that this does not have any significant influence.
The results show that no single personal characteristic has a significant influence on nudge compliance.

Overall, the finding that characteristics do not influence nudging compliance is favourable for practical uses. It means that nudging can be applied more generally and does not have to be adapted to the target demographic.

4.4.3 Directional bias

Theory suggests that people have a directional bias to the right (Bond, 2020)P179. This research confirms this belief. It is also of similar strength as found in previous research (Beek, 2024). Previous research could not find a reason for this directional bias. Based on theory, eye dominance and hand dominance would be of influence (Bond, 2020)P179.
This research has found out that this effect is in the opposite direction as expected according to theory. The effects found were not significant, but the fact that they all point in the opposite direction from literature merits further research.

5 Conclusion

This chapter concludes the research. First, the assumptions and caveats of the experiment are discussed. Second, all research questions are answered. Then, some practical recommendations are given and finally some research recommendations are given.

5.1 Discussion

There are a lot of caveats and assumptions made for this research. In this paragraph all factors that limit the effectivity of this research will be discussed.

It can be discussed whether the researched intervention methods are representative enough. This research addresses how important context is to the use of nudging. This study has made two significant assumptions in this regard. Firstly, the variants of the intervention methods could be worked out further. The current method variants are designed based on expert counselling but no actual theories. The selection of three variants is rather limited, so further research into the actual implementation of intervention methods is advised. Secondly, the context in which the intervention method is placed can greatly influence its effectivity. In the Netherlands a maple tree is totally normal whereas in Egypt it would be very much out of place.

The representativeness of the experiment environment can also be discussed. Is VR the correct method or does it come with great downsides? This study has found that the VR environment is a great way of exploring behaviour, but not perfectly fit to validate these behaviours. The VR environment cannot be made realistic enough to be fully seamless. The image quality is not great enough and factors like wind, sound, smell, and friction cannot realistically be copied. This makes the choices less representative overall. Even if the environment could be made fully seamless, the nature of a controlled experiment would still hurt its validity. Participants will always know they are in an experiment, and this changes their behaviour. The environment is also rather sterile so the effects of weather, familiarity in the environment and other road users are all not included. It is important to note that this is a conscious decision. Because of the explorative nature of this research, it was necessary to get this level of controllability. However, to fully validate these results, similar experiments should be set up in the form of field tests.

Finally, the representativeness of the sample can be discussed. Most participants were employees of Royal HaskoningDHV or students at the Delft University of Technology. This is not a representative sample of the whole of the Netherlands. This study has found that personal characteristics do not influence nudge compliance, but still it is advised to get a more representative sample in subsequent research.

5.2 Answers to research questions

The objective of this research is to explore the ways infrastructure can improve cyclist route choice behaviour, by the means of nudging. The main research question is:
How can infrastructure effectively be used to nudge cyclists to make specific route choice decisions?
The main research question is jointly answered by the following sub-questions:

1. What factors influence route choice according to literature?
2. How can the effects of nudging techniques effectively and efficiently be measured?
3. Which infrastructural interventions can be taken to nudge cyclist route choice?
4. What is the impact of infrastructural interventions on cyclist route choice?
5. What participant characteristics influence the effect of nudging on cyclist route choice?

These questions are answered in this paragraph.

What factors influence route choice according to literature?
There are a lot of different aspects that influence route choice behaviour. Some notable factors that influence route choice behaviour according to literature are distance and comfort. These aspects are both found to be very subjective. Different people view different situations as comfortable. Factors like amount of traffic lights, amount of turns and route complexity can make a route feel longer, which are also viewed differently by different people.
Some notable characteristics that influence these views are the following: age, gender and cycling experience. Older people tend to value safety more, women use visual cues more often to orient themselves and less experienced cyclists tend to be more rule following.
There are three main ways to influence people's behaviour actively: incentivising, educating, and nudging. The latter is not researched a lot yet and is found to be promising, thus is the focus of this research. Nudging affects people's behaviour by making them think that they made the decision themselves. By focussing on the subconscious of a person. Therefore, it can be an effective measure for changing people's behaviour if knowledge and fines/monetary incentives prove to be insufficient.

How can the effects of nudging techniques effectively and efficiently be measured?
There are a few ways to measure the effects of nudging. In this research a choice is made between doing a revealed choice experiment and a stated choice experiment. For this research a stated choice experiment is chosen since the research is exploratory in nature and the subconscious effects of nudging are known to fall off against environmental effects such as wind.
For this specific stated choice experiment a VR experiment with a physical bicycle setup is chosen. This is done to immerse participants as much as possible, since it was discovered that immersion is closely linked to experiment representativeness. The environment was also made as sterile as possible to isolate the effect of the nudging methods and know for sure that these are the only effects that change.
It is found that VR experiments are a very efficient way to measure the effects of nudging. A lot of different factors can be explored at once, and the ease of use makes it very flexible in testing new experimental design, however this method is not sufficient in validating cyclist behaviour. Since the environment is so simplistic in nature it cannot be said for sure that the behaviour in the experiment is the same in real life. Therefore, notable results should be tested in a physical experiment as well.

Which infrastructural interventions can be taken to nudge cyclist route choice?
There are a lot of different interventions can nudge cyclist route choice in theory. However, most methods are merely concepts and have not been tested in practice yet. A lot of these methods are not included in this study since they are thought to be too big of an infrastructural intervention, or merit more extensive research. These six intervention methods are conceptualised but not included in the experiment:

- Changing the openness of an area, by making spaces more or less spacious.
- Adding arbitrary landmarks, to lead people by.
- Looking further into the location where route signs are placed.
- Working with colour.
- Working with lighting conditions.
- Working with sound cues.

These experiments are included:

- Hierarchy: leading people with stripes on the ground.
- Obstruction: Limiting vision on the intersection to lead people a certain way.
- Herding: Having imagery of creatures moving in a certain direction to lead people in that direction.

For all three methods, three iterations were made to test intensities and practice cases.

What is the impact of infrastructural interventions on cyclist route choice?
Obstruction methods are not effective in nudging people's behaviour. There are too many different interpretations possible. In general, more people got attracted by these obstruction methods rather than deterred from it. This method works better on less experienced cyclists. They are more concerned about their safety and are deterred by the decreased vision, though still not significantly so.
Herding methods work quite well. All variants are successful in nudging cyclists. However, more abstract paintings only work to the right. This is happening because herding affects people more when the drawing is more human-like. The more abstract painting nudges people through deflection, which works better to the right.
Hierarchy methods work the best. This method is already used in practice quite often, so this research further enforces its effectivity. It was found, however, that making the desired road a different colour did not work as well as expected. This is quite peculiar since this form of nudging is currently used in practice quite often.

What participant characteristics influence the effect of nudging on cyclist route choice?
A lot of human aspects were theorised to have influence on route choice behaviour; however, this experiment has found that human aspects do not influence people's route choice behaviour. Gender, age, height, country of origin, etc. do not have impact on people's route following behaviour. This means that nudging can be used on everyone and achieve similar effect.
One human aspect does influence route choice quite a lot is directional bias. People are generally compelled to turn right if no other factors nudge them into a certain direction. This effect becomes weaker when nudging is applied but does not fully go away. Up to 62% of people turn right if no nudging is applied, and with nudging applied, still 56% of people turn right. This seems to be the same for all people. Theorized factors of effect such as dominant hand, dominant eye and on which side of the road people usually drive have no significant influence on this directional bias. This means that nudging people to the left will always be harder than nudging people to the right.

5.3 Practical recommendations

This paragraph discusses the practical implications of this research. It is very important to note that this research is exploratory in nature. This means that most found results do not have direct practical implications. Most implications are of a research nature, however there are still some practical recommendations to Royal HaskoningDHV and other engineering firms that are reading this.
First, truncations and curves on the road work very effectively. These methods are already in use and are therefore recommended to keep. Not only are these methods very effective. They are also widely applicable and cheap to implement. It is recommended to keep using these methods to guide bicycle traffic flows.
The differently coloured roads however have been found not as effective. This research recommends engineering firms to do research whether these methods work. This can be done at locations where this method is already in place. If it does not work, it can be enforced by introducing a white curve.
It is also recommended to consider the implication of herding in nudging practices. It is important to note that this method is still experimental, so it should be used with caution. However, in some situations it could be a very good addition that can nudge cyclists in a creative way, which can also add to the aesthetic quality of a city if done well. An example of an application is to add street art of sports cyclists to promote fast cycling routes.
Finally, it is important to always keep in mind the context of the specific intersection before applying a nudging method. Since these methods lean so heavily on the subconscious of people, they can be influenced by numerous things that are not included in this research. Application of nudging methods should always be evaluated on a case-to-case basis to make sure it is done correctly.

5.4 Research recommendations

There are a lot of research recommendations to be given. This paragraph gives a list of topics that require further research. They are sorted in order of priority.

This study has found that hierarchy and herding are effective methods of nudging cyclist route choice. Subsequent research should perform a field test to validate these results. This way, it can be seen if these methods are useful in practice.

This study has tried to find an explanation for the directional bias but failed to do so. It does suggest that factors like eye and hand dominance have the opposite effect from what theory suggests. This effect is not significant, but multiple factors were all pointing in the opposite directions from literature. It is recommended to perform further research into this phenomenon, as it also could test if increased brain activity in the left and right brain half influences this behaviour.

This study has found a rather odd phenomenon which suggests that herding becomes less effective when the intervention becomes less human. It is very much recommended to perform more in-depth research into whether this is the case or not.

Finally, this study found that VR experiments are very effective in exploring whether intervention methods can have significant effect on cyclists. It is recommended to perform research into the methods that were not researched in this study. In general VR enforced stated choice experiments can be performed to get insight into the effect that colour, light, sound, and movement have on cycling behaviour.

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Studying the effect of infrastructural nudging on cyclist route choice behaviour using virtual reality

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Abstract

Cyclist route choice can lead to uncomfortable and dangerous situations. Therefore, it is important to research ways to influence this. This study explores how infrastructural nudging can be used to influence cyclist route choice. Using virtual reality and a bicycle simulator the impact of visual road hierarchy, visual obstruction and herding through street art is studied. A virtual urban environment was designed with 11 T-intersections. In 9 of the 11 intersection these methods were applied in three different ways, to see whether the nudge impacted cyclist route choice. The gathered data was then analysed with descriptive data analysis and discrete choice modelling. This study shows that cyclists follow nudges using visual road hierarchy and herding. However, they do not follow nudges with visual obstruction. This effect is the same for people of all ages, genders, heights etc. Though less experienced cyclists seem to react more heavily to obstruction methods. The results also indicate that cyclists have a significant right-handed tendency. This effect is not influenced by eye or hand dominance. The effect becomes slightly weaker when nudging is applied but does not go away. Future research should validate these results in a physical environment before this is used in practice.

Introduction

Cycling is a very common means of transport. In the Netherlands it is the second most used mode of transport, just behind the car (CBS, 2021). To ensure safety and comfort, it is important to have sophisticated infrastructure and well laid out rules. In the last five years fatal cycling accidents have been rising sharply (NOS, 2023). This rise is mostly seen in the elderly community. The rise in fatal accidents raises the need for better research and guidelines. Especially now that bicycle use is increasing drastically throughout the world. Since the corona epidemic bicycle use has been skyrocketing in almost every country (Bernhard, 2020). With the Netherlands being the frontrunner in bicycle research it is important to expand our knowledge as much as possible to provide a well-built cycling infrastructure.

Even though research into the safety of vulnerable road users has been steeply increasing (Scarano et Al, 2023), there are still parts which are overlooked. Research mostly focusses on safety whilst cycling a certain route. Route choice itself can be a catalyst to accidents as well. (Mesimaki, 2021) state that most pedestrian cyclist (near) accidents occur on pedestrian streets. Cyclists being in unfavourable places pose a threat to safety and efficiency and should therefore be avoided as much as possible.

People's choices can be influenced in three different ways; incentivizing, informing, and limiting the choice space (nudging) (Hansen, 2016). A plethora of research investigate the effects of incentivizing and informing, but research into the effects nudging has been lacking.

Nudging is a form of limiting people's choice space without them knowing. In a cafeteria for example the unhealthy snacks can be laid behind the fruits, so people are enticed to grab the food rather than the unhealthy snacks (Thaler, 2008).

Nudging has been used sparingly in the transportation sector in the past. Nudging with transverse stripes and by lowering vision has been used to lower cyclists and drivers approach speeds to significant success (Kovaceva, Jordanka, 2022), (Charlton, 2003). Colour has been used to improve cyclist salience and to increase the desire to use a bike (Fyhri, 2021), (Chen, Jun, 2023). Light has also been used to influence pedestrian route choice to significant success (Buikstra, 2021), (Beek, 2024). These studies show that nudging can be effective in the transportation field. Therefore, this research will explore if nudging can be used to influence cyclist route choice.

The objective of this research is to explore the ways infrastructure can improve cyclist route choice behaviour with nudging. This is achieved by answering the following main research question:

How can infrastructure be used to nudge cyclists to make specific route choice decisions?

The main research question is jointly answered by the following sub-questions:

- What factors influence route choice according to literature?

- How can the effects of nudging techniques effectively and efficiently be measured?
- Which infrastructural interventions can be taken to nudge cyclist route choice?
- What is the impact of infrastructural interventions on cyclist route choice?
- What participant characteristics influence the effect of nudging on cyclist route choice?

This research will focus on T-intersections in urbanized area, since these intersections favour the most from better guidance. It will not include factors like distance, familiarity, and other road users. The experiment will use Virtual Reality (VR) to efficiently model the effect of some of the most promising structural interventions involving nudging. This study is one of the first studying the effect of infrastructural nudging on cyclist route choice. It is exploratory in nature and should be followed by further research in the field. The rest of the paper is structured as follows: Section 2 discusses the findings of previous research regarding cyclist behaviour and intervention strategies. Section 3 presents the research methodology, including experiment design, experiment setup, experiment procedure, data collection, data analysis and participant characteristics. Section 4 presents the results of the study and links it previous studies. Finally, section 5 gives a conclusion and recommendations for future research.

1. Theoretical framework

A thorough literature review is performed. This chapter discusses key aspects and underlying theory.

1.1. Infrastructural aspects influencing route choice

There are a lot of aspects in infrastructure that influence people's route choice. Cycling and driving behaviour are very subjective matters. They can be influenced by all kinds of different factors. (Segadilha, 2014) found that factors like number of buses, traffic density and traffic speed are big factors in deciding cyclists route choice.
An important factor is perceived safety. Cyclists value their own safety but do seem to overestimate their own capabilities which can lead to them making risky choices. (Shaw, Louise, 2015) found that cyclists often break traffic rules because of self-determined poor infrastructure design.
Another important reason for risky routing decisions is distance. (Law, 2014) suggest that directness is more important to route choice than safety and comfort. (Song, 2017) have done a study into the risky route choices of cyclists. A thought experiment was conducted where a cyclist had to take a small detour to get to a traffic light to cross the street. The longer this detour became, the more people broke the rules and crossed the street without a traffic light.
Since distance is a subjective matter, perceived distance plays an even bigger role. A study by (Nohad, 2008) reveal that cyclists do not always take the shortest paths possible. (Dalton, 2015) discovered that the average bicycle trip is 27% further than the shortest option. Cyclists prefer paths with dedicated cycling infrastructure and with few interacting traffic. They also prefer paths with the least decisions to be made. Therefore, paths with few turns are felt shorter and are more popular to cyclists (Bond, 2020)P193.

1.2. Personal characteristics influencing route choice behaviour

Different humans react differently to impulses. Human aspects like age, gender and eye dominance can be of influence on how people react to the built environment (Bond, 2020)P99. Factors like employment, house ownership and physical health have all been researched in the past, but no correlations have been found (Dalton, 2015).
The human characteristic which is thought of most commonly to influence behaviour is gender. Gender plays a role in wayfinding strategies, although most of these differences come through nurture rather than nature (O'Connor, 2019), (Bond, 2020)P125. Safety is found to be somewhat more important to women than men (Prati, 2019). Also, female cyclists are more sensitive to lighting conditions than men. Women also rely more on the environment and less on spatial clues like distance when wayfinding (Bond, 2020)P123. This suggests that different genders could react differently to nudges in the environment.
Age is another human factor which is of influence on route choice behaviour. (Stinson, 2003) state that comfort and traffic conditions are the most important factors to older people whereas distance is found to be the most important amongst younger people when wayfinding.
There are also multiple factors that can influence the tendency of people to move either right or left. (Beek, 2024) found that people have a right-handed tendency. When no nudging is put in place 53% of all participants turn right. The article also states that this tendency dissipates whenever nudging is used. It is speculated that this tendency can come from people driving on the right side of the road or people being right-handed. (Bond, 2020)P179 state that eye dominance has an impact on route choice. They found people with a dominant right eye are more likely to turn right when their straight path is obstructed, for example when they face a cliff in a desert.

1.3. Methods to influence route choice behaviour

People's choices can be influenced in three different ways: by incentivizing favoured choices, by education, and by limiting the choice space (Hansen, 2016). In psychology this last method is often called paternalism. These three possibilities of choice diversion are explained further in this paragraph.
Incentivizing favourable choices is the most straight forward way of changing people's behaviour. As already discussed, people tend to use the route which is fastest. If the favourable route is made the fastest one, more people will take it. Monetary incentives can also be used. (Bie, 2009) state that monetary incentives are successful in changing route choice behaviour for car traffic. Another common way of incentivizing favourable route choices is by discouraging unfavourable ones. Laws and regulations with

patrolling officers and fines are what drives safety to be a priority amongst motorists (Lyndel Bates et Al., 2012). It is, however, not always possible to make the preferred road quicker, especially in a city centre. Monetary incentives and more law enforcement costs a lot of money, so other methods are also used.

Another method to change choice behaviour is education. A driver cannot make the right decision if it does not know what it is. One of the most common uses of this is traffic signs. Each traffic sign informs the road user what is the favourable or required course of action. A more involved way of informing road users is by using real-time route diversion (Spiliopoulou, 2018). This system detects where traffic jams are bound to occur and diverts traffic to less congested roads. Almost every navigation system uses such systems nowadays. Informing does not always prove useful for cyclists. Research points out that cyclists often break traffic rules, even when they are correctly informed (SWOV, 2023), (Shaw, Louise, 2015). This means that informing works less well for cyclists than it does for cars.

A third way of changing behaviour is by limiting people's choices. In psychology this is often called paternalism. *"Paternalism is the interference of a state or an individual with another person, against their will, and defended or motivated by a claim that the person interfered with will be better off or protected from harm."* (Stanford, 2020). Paternalism is all about limiting the choices of individuals to improve their wellbeing. A paternalist would modify a car to make driving over the speed limit literally impossible. There are two main forms of paternalism. Hard paternalism and libertarian paternalism.

Nudging falls under libertarian paternalism. (Hansen, 2016) clarify that a nudge is an intervention that changes people's behaviour without limiting any choices nor giving any economic incentives. (Sunstein, 2003) argue that people are very poor decision makers. They should be nudged in making the right decisions or are bound to make the wrong ones. Nudging is proven to be an effective way of influencing decisions of cyclists and pedestrians (Bandsma, 2021). Critics advice governments to use these methods sparingly and only when their effects are well documented, since the views on its use are not always positive (Elvebakk, 2015). Therefore, it is important to perform thorough research into the use of nudging methods.

1.4. Exploring intervention methods

Infrastructure has not been used yet systematically to influence cyclist route choice. However, there are a lot of concepts in literature that can prove to be effective in achieving this. This paragraph provides a comprehensive list of possible intervention methods, along with a synthesis into the theories on which these are based.

1.4.1. Obstruction

Obstruction is the first possible form of nudging. It involves blocking the sight to one of the possible exits to make it less favourable of a choice. (Charlton, 2003) show that lowering visibility is an effective way of lowering drivers' approach speed. This does not only influence speed. (Gath-Morad, 2021) show that pedestrians do the same when wayfinding. If the desired end location is in sight, they directly lock on and go there. When the location is not directly visible, they tend to wander before deciding. This behaviour can be harnessed as a form of screening (Cullen, 1961). By making the road to the right pop out more a decision is enforced.

1.4.2. Hierarchy

The second form of nudging is by imploring directness. (Dill, 2008) found that cyclists do not always take the shortest route. In a lot of situations, they take the route that feels the fastest. The process of making routes more enticing like this is often called hierarchy by employees of Royal HaskoningDHV. With bumps and barriers, a physical hierarchy is created, and cyclists are guided in the right direction. This hierarchical structure can also be implied less intrusively. By suggesting the right course of action with colour or road markings a path is made. People often tend to follow paths, even if these paths are just suggestions. (Bond, 2020) P51 reveal that animals are biologically bound to adhere to this trait. (Lynch, 1959) also state the importance of boundaries in wayfinding procedure.

1.4.3. Attractiveness, deflection and herding

The third possible intervention method combines two psychological concepts: the effect of deflection and herding.

Deflection is a concept from urban design. It involves hiding information from a person to entice them to look further. If a building is placed in such a way that it seems to continue further than what is visible it entices people to go there and check it out (Cullen, 1961). This concept has not been used for nudging before but this can be experimented upon.

The other concept involves herding behaviour. (Thaler, 2008) P53 suggest that people's behaviour can be strongly influenced by other people. Phenomena like obesity rate and college performance strongly depend on the actions of those around you. Herding behaviour is often seen in the movement of animals, where animals like sheep and fish always try to remain in the crowd. This form of choice manipulation has been used in environmental studies to great success (Wee S.-C. , 2021). By for example placing footsteps on the ground leading towards a trashcan, they could greatly decrease the amount of street littering.

1.4.4. Sign placement

The next intervention method is sign placement. The information given is not a form of nudging, since it is defined as informing, but the presence of these signs can do more than merely giving information. A sign meant for pedestrians could also have effect on cyclists. The mere presence of an arrow to the right could entice them to go that way. Furthermore, the location of these signs could also have influence on the route choice of cyclists. The location of signage is important to their effect. These signs should be placed on key decision locations to have the most effect.

1.4.5. Openness

Another method of wayfinding which is grounded in psychology is openness. People tend to want to move to open spaces. This can be used in two different ways.
First, an area can be made less open. By restricting the openness with either a tunnel or just making a street narrower an imaginary wall is created (Cullen, 1961). This disincentivises people from going down this route.
The second way is by making space more open. Squares can be attractive for people, especially if certain activities are committed there. It can play on their sense of place (Žlender, 2020). A square can however also deter cyclists since the effect of possession can make the space feel as a pedestrian only zone.

1.4.6. Anchor points

People often use locators during the wayfinding process (Lynch, 1959). (Yesiltepe, 2021) people use global landmarks like towers to navigate and orient themselves. Other than being a key factor in orienting for people, landmarks like towers can often become the focal point of an area (Cullen, 1961). These focal points often drag people in, therefore changing their wayfinding behaviour. This could be used in our favour, by placing artificial towers and landmarks in key locations people could be nudged in the desired direction.

1.4.7. Light

Another effective way of nudging people's behaviour is by using light. (Hidayetoglu, 2012) found that roads with bright lights are more positively perceived. This positive reaction does not only raise the individual's wellbeing but also actively influences orientation preferences. (Beek, 2024) found that pedestrians actively move towards areas with brighter light. It remains a question if this effect also works on cyclists.

1.4.8. Colour

Another intervention method using nudging is making use of colour. One possible way of using colour is by painting the sides of buildings specific colours. (Hidayetoglu, 2012) say that people tend to walk to warmer colours, whereas (Beek, 2024) suggest that people tend to move towards green lights and away from red.

1.4.9. Sound

The final possible method explored in this research is sound. (Asutay, 2019) state that sound is a big catalyst for emotion. Since emotion is an important factor on cycling behaviour (Roidl, 2014). Sound could be used to nudge wayfinding. (Freriks, 2015) tried to use music to nudge people into making healthy food purchases, but to no avail.

1.4.10. Summary

To summarise, this study identifies 9 possible methods of nudging cyclist route choice. It is possible that other methods can also prove to be effective but the nine methods presented here are all supported by enough theory to be considered. This study will select a few of these methods in section 2.2.1 but all methods mentioned here merit further research.

2. Methodology

This chapter describes the methodology used to answer the main research question. It will explain the research design, experiment design, experiment setup, experiment process, data collection, data analysis and participant characteristics.

2.1. Research design

The aim of this research is to explore the ways infrastructure can improve cyclist route choice behaviour with nudging. To achieve this a Virtual Reality (VR) experiment is conducted and analysed. First, literature reviews and expert counselling are used to acquire sufficient knowledge into the subject. With this knowledge a set of possible intervention methods is constructed. A VR environment is constructed, and these intervention methods are implemented within this environment. The literature review also identifies human characteristics important to cyclist route choice. With these aspects a questionnaire is constructed to be held before the VR experiment. Then the experiment is conducted and analysed in a discrete choice analysis. This way the effects on route choice of every intervention method can be described.
Expert counselling is used as an input since research is lacking in the field of this study. Employees of Royal HaskoningDHV are interviewed with a theory-generating expert interview where research is lacking (Döringer, 2021).

2.2. Experiment design

A VR experiment is used in this research. Three other research methods were considered but not used; field observations, surveys and controlled physical experiments (Feng Y. , 2021).
Field observations lack the needed controllability (Feng Y. , 2021). It is hard to measure the effects of nudging in real life scenarios because of uncontrollable factors like wind (Kovaceva, Jordanka, 2022).
Surveys are not representative enough (Feng Y. , 2021). People do not always make the same choices as stated in surveys. This can especially be a problem for subconscious decisions, which nudging methods aim to influence.
Controlled experiments are not chosen since they can be very expensive and take a long time to implement (Feng Y. , 2021).
VR is chosen since it is controllable in nature whilst being less expensive than controlled experiments and more immersive than a simple survey (Mokas, 2021).

2.2.1. Defining intervention methods

Paragraph 2.5 presents a list of possible intervention methods. Together with several employees of Royal HaskoningDHV the most promising methods are selected to be researched. In the VR experiment a total of 11 intersections can be tested, since the risk

of choice exhaustion becomes too high with more choices as stated by the XR Zone team of Delft University of Technology. Therefore, it is important to only research what is most necessary and promising. This paragraph presents all intervention methods and why some were left out.
three intervention methods are tested with three variants each. This is done since three interventions stood out the most and it is important to test each method multiple times, to make sure it has effect. Consequently, it can also be investigated whether different variants of the same method work differently.
The methods that were not chosen include: Sign placement, openness, anchor points, light, colour, and sound. These methods were not included since they required very large infrastructural interventions or required more extensive research to validate their use.
The three chosen intervention methods are obstruction, hierarchy, and herding.

Obstruction

Obstruction involves blocking the view of one of the two directions to make the other feel more enticing. Three different objects are chosen to obstruct the view in the experiments. All three objects are objects that are often seen in the city image. A tree, a hedge and an add-sign.

Figure 1 Tree (left), bush (middle), add-sign (right)

The tree is chosen since it is found to be the most promising by the author. It provides a large barrier without negatively impacting the environment visually. If placing a tree is found to be an effective nudge it will be a popular choice for municipalities, since municipalities are already obliged to add more trees in the city centre.
The bush is chosen since it blocks the bottom side of the view instead of the top side of the view. Since the hedge blocks the view of the road more it is hypothesized to have a larger effect than the tree.
The add-sign is thought to have the weakest effect. Still, it is added, since adding an add-sign like this by far takes the least effort. If it is successful in nudging cyclists, it could be used immediately.

Hierarchy

Hierarchy involves introducing a hierarchical structure in the roads. By creating a physical barrier in between two roads, with colour, stripes, or traffic bumps one road is formulated as being the main road compared to surrounding roads.
This method is found promising since it requires little infrastructural intervention. this method is already used very often, but no empirical research has been done into the effects of it. Municipalities are more often asking for empirical research, so this research could help enforce the effectiveness of this method. This method is also thought to be the most effective method by a big margin. The three chosen variants are: colouring one road part, adding a white diversion curve, and adding truncations.
These three methods are chosen because they have an increasing amount of guidance. This way it can be derived whether the level of guidance is important to the nudging strength.

Figure 2 Road colour (left), white curve (middle), truncation (right)

Herding

This specific application of herding involves introducing imagery of creatures or objects moving in a certain direction. Due to herding behaviour people are coerced to move in the same direction. This method is applied with street art. This method also uses the effect of aesthetics and deflection. Herding is already used a lot in urban environments for other goals and is documented to work well there. Furthermore, adding art to an intersection is something municipalities would be eager to agree to according to employees of Royal HaskoningDHV. It is important to note that herding does not have to be done with street art but can also be done with statues or other pieces of art. Street art is merely chosen since it was easy to implement in the experiment environment. The three nudging methods are: a piece of art of a cyclist, a fish, and a wave.

Figure 3 Bike (left), fish (middle), wave (right)

In the past, herding has only been applied with drawings of human like figures. These three variants are chosen to explore the effect of abstraction on herding strength. Is it possible to influence people with any kind of drawing or do the drawings have to be of humans?

2.2.2. Design of the virtual environment

The virtual environment is designed to make people feel like they are in a Dutch urban environment, since participant immersion is important to the representativeness of the results (Bogacz, 2020). It is kept a rather simple environment to reduce the factors influencing cyclist route choice. This is especially done near decision points.

The width of the road is 5,8 meters. This is the required width for a two-way car/bike shared street as registered by the CROW. The sidewalk is made to be 2,4 meters wide on both sides.


Figure 4 Virtual environment

The buildings are modelled to resemble buildings in a typical Dutch neighbourhood as much as possible, whilst still being simplistic to avoid entering the uncanny valley (Mathur, 2016).

At every turn the Field Of View (FOV) changes from 96 degrees to 60 by introducing a vignette. (Kim, 2018) conclude that this is the best way to reduce the risk of motion sickness whilst keeping the level of immersion as high as possible.

2.2.3. Design of the experiment

The experiment is set up in a specific way. The participant is told to go to the river at the other side of town. However, they are put through 11 intersections where they must go left or right. The experiment starts with the base scenario and ends with the base scenario. This is done to snuff out any directional biases of the participants and to account for the effect of choice exhaustion. This means that there is room left for 9 experiments. Employees from the XR zone team state that choice exhaustion becomes apparent after 11 to 16 choices in an experiment of this notion, so a value of 11 has been chosen to be safe.

The experiment models the effect of the nine nudging variants as discussed in section 3.3.2. No interaction effects are tested, since this would make the experiment very large.

Figure 5 shows the road setup that is used for the experiment. Every time the participant chooses a direction, more roads are generated in only that direction. This way every participant gets the same order of intervention methods, no matter what direction they choose. Each turn is followed by a turn back, so people keep going straight. This is done to reduce bias. If the participant would not be turned back it would feel like they are going in circles, and they would correct for this to keep going straight.

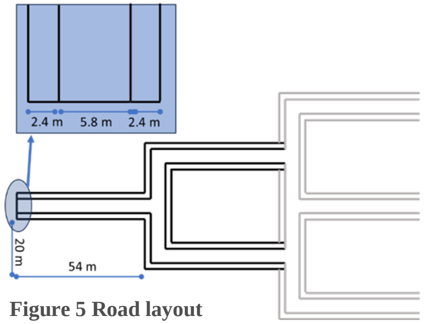

Figure 5 Road layout

Still this method could induce some bias. The participant does not return to the exact width that they were when deciding. This causes them to veer to one side when choosing the same direction multiple times. Every intersection veers 20 meters so in total they veer of 220 meters if they always choose the same direction. A different version was tested that fully eliminated this bias but, since it introduced too many turns it was scrapped to reduce the risk of motion sickness.

There are two versions of the experiment. A normal version and a flipped version to eliminate directional bias.

Table 1 Nudging methods and direction

Intersection	Intervention method	Direction	Direction (flipped)
1	No intervention	None	None
2	Bush	Right	Left
3	Coloured road	Right	Left
4	Bike	Left	Right
5	Curve	Left	Right
6	Tree	Left	Right
7	Wave	Right	Left
8	Add sign	Left	Right
9	Fish	Right	Left
10	Truncation	Right	Left
11	No intervention	None	None

2.2.4. Experiment setup

The participants were immersed in the virtual environment with an HTC Vive. The system consists of a Head Mounted Display (HMD) with one base station and two hand controllers. The two controllers are strapped to the bike simulator used in the experiment. Other HMD's were considered but not chosen since the HTC Vive controllers fit the best on the bicycle simulator.

The VR environment runs on Unreal Engine 5.1 and Steam VR. The game engine and VR software run on an Intel I9-12900hk CPU and an NVIDIA Geforce RTX3080TI graphics card.

The bicycle setup is controlled using a Raspberry Pie and the Tackx system. The Tackx system is often used for cycling training for sports cyclists since it can realistically introduce road drag. It is however not very quick. It has a delay of 3 seconds between input and output. For sports cycling this is no problem, but for realistic experiments it can pose trouble. Therefore, the setup has been modified with a Raspberry Pie. The Raspberry Pie has been programmed by by Dr. Yan Feng and XR Zone at Delft University of Technology with a plugin to monitor the speed of the bicycle. This system has a delay of 0.01 seconds to give a realistic real time representation.

The participants can turn the bike in VR by pressing buttons on the controllers. These controllers are strapped to the handlebars with rubber bands and tape, for easy removal. A basic table fan blows wind in the face of participants to reduce motion sickness and increase immersion. As (Chang, 2020) state, an effective measure of reducing motion sickness is by creating multisensory input.

2.2.5. Experiment conduction

This VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 4336). The recruitment involved sending emails, posting on social media and spreading flyers. People were also recruited physically during the experiment. Therefore, the experiment was kept purposefully short. All participants joined the experiment voluntarily. The experimental procedure consisted of three parts: the introduction, the VR experiment and the post-experiment questionnaire.

Figure 6 Experiment setup

Introduction (5 minutes). The experimental procedure was communicated to the participants with a written statement. In this statement the possible risks of the experiment were explained. Participant needed to sign this consent form to perform the experiment.

VR experiment (10 minutes). Participants took place on the bicycle simulator and were equipped with the VR headset. They got time to adjust settings on the VR headset to fit them optimally. They were then put in a VR test environment, which is the same as the actual experiment but without nudges present. Here they were able to familiarize themselves with the controls and get used to the sharp turns. When they indicated to be ready, they were put in the formal experiment. Odd participants were put in the normal environment and even participants were put in the flipped version. In this experiment participants were tasked to get to the other side of town by choosing what way to go on intersections. When they got to the exit the experiment was stopped, participants got time to rest and were then asked to participate in the post-experiment questionnaire.

Post-experiment questionnaire (15 minutes). After the experiment participants were asked to fill in the questionnaire described in section 3.5. This questionnaire consisted of three parts: a part related to personal characteristics, a Presence Questionnaire (PQ) (Witmer, 2005) and a System Usability Scale questionnaire (SUS) (Brooke, 1996). Participants that were short on time were allowed to skip the PQ and SUS questionnaire. After the questionnaire was complete the experiment was done, and participants were rewarded with a small snack. Five participants did not complete the experiments because they got motion sick.

2.2.6. Data collection

Both qualitative and quantitative data is collected. The VR environment collects quantitative data. This includes participants decisions and head rotation at every frame of the experiment. Each experiment is also recorded in OBS. The questionnaire collects qualitative data. This includes participant characteristics, their feeling of presence and the usability of the VR system. Finally, notable qualitative results are also written down. Participants are asked for their reasoning behind some choices for example. This data is used for the qualitative analysis.

2.2.7. Data analysis

The data analysis consists of four parts: data formatting, a qualitative analysis, a descriptive analysis, and a model analysis. The data is formatted in Python, the descriptive analysis will be performed in SPSS and the model analysis in RStudio. Some redundant and unused data such as head direction are removed from the dataset and the rest of the data is encoded for further use.

Binary data points such as turning direction are dummy coded (Moutinho, 2013). The values left, female and yes are coded 1 and the values no, male and right are coded 0. Ordinal data such as cycling frequencies are coded from 1 to 5.

Some interesting qualitative findings during the experiments are written down and are included in the discussion of the results.

For the descriptive analysis a χ^2 test is used (Singhal, 2013).

For this χ^2 test FollowNudge is used as the dependent variable. FollowNudge is a binary variable that returns a value of 1 of the nudge is followed and 0 if the nudge is not followed or is not present. A confidence interval of 95% is required to deem an effect significant. This descriptive analysis is performed to find general patterns and notions in the data and will be followed by a model analysis.

For the model analysis a Multinomial Logit (MNL) model is performed in Rstudio (Maalouf, 2011). MNL is a form of logistical regression analysis specialized at estimating complex relations between a nominal dependent variable and multiple independent variables. Two more sophisticated methods were considered. Mixed Logit (Hensher, 2011) and Latent Class cluster modelling (Hess, 2011) were both not chosen since the relatively simple dataset did not require such intricate modelling.

$$U1(Left) = \quad Nl * Func$$
$$U2(Right) = DB + Nr * Func$$
$$DB = \beta_0 + \beta_{el} * DomEyeLeft + \beta_{er} * DomEyeRight + \beta_{hr} * DomHand + \beta_{rr} * RoadSide$$

For the MNL model a utility function is set up. This utility function has ChoseLeft as a dependent dummy coded variable. ChoseLeft returns 1 if the participant turned left and 0 if they turned right. FollowNudge is not the dependent variable since there are situations in which no nudging is in place. FollowNudge would then be 0 by default and this data would make the rest of the results invalid. A directional bias (DB) is introduced in the utility function to the right since it is expected to point to the right. This DB consists of the variables DomHand, DomEye and RoadSide (the side on the road that people travel in their country of origin). This model checks whether people follow the nudge by introducing the dummy coded variables NudgeLeft (Nl) and NudgeRight (Nr). The function ($Func$) that follows is the same in both directions and is explained below.

$$Func = (Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd)$$
$$Obs = \beta_{Tr} * Tree + \beta_{Bu} * Bush + \beta_{Ad} * Add$$
$$Hier = \beta_{Ro} * Road + \beta_{Cu} * Curve + \beta_{Tu} * Truncation$$
$$Herd = \beta_{Bi} * Bike + \beta_{Fi} * Fish + \beta_{Wa} * Wave$$
$$Char = (1 + \beta_{Char} * Characteristic)^{**}$$
$$^{**}With\ different\ \beta\ for\ the\ 3\ different\ interactions\ and\ a\ factor\ for\ each\ characteristic$$

This function describes all intervention methods and the characteristics that may influence their effectiveness. The intervention methods are split up in the three different nudging methods: obstruction (Obs), hierarchy ($Hier$), and herding ($Herd$). Each nudging method is expected to interact differently with the characteristics. Therefore, each characteristic ($Char$) has three different β for the three interactions (shown as $Char.obs$, $Char.hier$ and $Char.herd$). The considered characteristics are age, gender, height, cycling experience, and whether people knew that they were being nudged.

This results in the final utility function:

$$U1(Left) = \quad Nl * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$$
$$U2(Right) = DB + Nr * ((Obs * Char.obs) + (Hier * Char.hier) + (Herd * Char.herd))$$

$$Obs = \beta_{Tr} * Tree + \beta_{Bu} * Bush + \beta_{Ad} * Add$$
$$Hier = \beta_{Ro} * Road + \beta_{Cu} * Curve + \beta_{Tu} * Truncation$$
$$Herd = \beta_{Bi} * Bike + \beta_{Fi} * Fish + \beta_{Wa} * Wave$$
$$DB = \beta_0 + \beta_{el} * DomEyeLeft + \beta_{er} * DomEyeRight + \beta_{hr} * DomHand + \beta_{rr} * RoadSide$$
$$Char = (1 + \beta_{gobs} * Characteristic)$$

2.2.8. *Participants characteristics*

In total 106 participants took part in the experiment. 5 participants stopped the experiment because they got motion sick and 2 participants were excluded since they solely turned left or right during the experiment, so 99 participants were deemed to have valid results.

From these participants 33 were female and 66 were male. The age varies between 18 and 70 with an average age of 31. Most participants (62%) cycle every day. Furthermore, most participants (70%) have almost never used a VR system, and quite a big portion (43%) of participants play video games often. There was no question about education level, but since most participants were either students from Delft University of Technology or employees of Royal HaskoningDHV the average education level is assumed to be high. It is important to note that 70 of the 99 participants guessed the purpose of the experiment correctly. The participant characteristics are summarized in Table 4.

The participants perception of the VR environment is evaluated with the Presence Questionnaire (PQ) and the System Usability Scale (SUS). The PQ evaluates the participants sense of presence by asking 29 questions on a 7-point Likert scale (Witmer, 2005). The average total score of the PQ is 123,49 (SD = 17,67). This indicates that the participants had quite a good sense of presence in the virtual environment. It is higher than several similar (Deb, 2017), but lower than some others (Beek, 2024). The PQ score has been split out in the four sections in Table 3.

Table 2 PQ score sections

Section	Average score	Standard deviation
Involvement	4.48	0.80
Sensory fidelity	3.46	1.00
Immersion	5.30	0.75
Interface quality	3.67	1.02

Table 3 Participant characteristics

Descriptive information	Category	Number (percentage)
Gender	Male	66 (66,67%)
	Female	33 (33,33%)
Age	<20	3 (3,03%)
	20-25	33 (33,33%)
	26-30	34 (34,34%)
	31-40	13 (13,13%)
	>40	16 (16,16%)
Cycling Frequency	Never	5 (5,05%)
	Less than once a week	6 (6,06%)
	1-2 times a week	6 (6,06%)
	3 times a week or more	20 (20,20%)
	every day	62 (62,63%)
VR Experience	Very often	3 (3,03%)
	Often	3 (3,03%)
	Neutral	23 (23,23%)
	Barely	45 (45,45%)
	Never	25 (25,25%)
Game Experience	Very often	20 (20,20%)
	Often	23 (23,23%)
	Neutral	30 (30,30%)
	Barely	25 (25,25%)
	Never	1 (1,01%)

In general, sensory fidelity and interface quality were rated the lowest. Participants had trouble with correctly adjusting the screen sharpness, so the vision was blurry for some participants, therefore interface quality scored lower. Sensory fidelity scored low since a lot of questions were about sound design. Sound scored low since it was not a focus of this research. The background sounds were often not noticed, and the sound that the bicycle simulator made was quite loud which was found to be distracting for participants.
The SUS questionnaire determines the usability of the system. It consists of 10 questions which are all answered on a Likert scale of 1 to 5. This score is then multiplied by 2,5 up to a maximum scale of 100. The average total SUS score is equal to 73,09 (SD = 6.72). This indicates that the VR environment has a 'Good' usability (Bangor, 2009). This result is slightly lower than the research by (Beek, 2024) but higher than (Feng, 2021).

3. Results

Table 4 Effectiveness and significance of every nudging method

Method	Effectiveness (total) (%)	Chi-Square (χ^2)	Significance (p)	Effectiveness (Right) (%)	Effectiveness (Left) (%)
Obstruction					
Bush	55.6	1.37	0.242	58.8	52.1
Tree	40.4	3.97	0.046	52.1	29.4
Add sign	49.5	0.01	0.942	68.8	31.4
Hierarchy					
Road colour	57.6	2.53	0.112	49.0	66.7
White Curve	72.7	22.59	<0.001	72.9	72.5
Truncation	74.7	26.78	<0.001	74.5	75.0
Herding					
Bike	64.6	9.40	0.002	66.7	62.7
Fish	66.7	12.17	<0.001	72.5	60.4
Wave	67.7	13.68	<0.001	80.4	54.2

This section presents the findings of the experiment. First, the impact of obstruction methods is discussed, followed by the effect of hierarchy methods and herding methods. Then, the impact of personal characteristics. Finally, the impact of directional bias is explored.

3.1. Impact of obstruction

Obstruction involved placing objects on the intersection to restrict view of one of the two intersections. The three variants are: placing a bush, placing a tree, and placing an add-sign. Overall, it is found that is method is ineffective.
Insignificant effects are found for the use of a bush *(p = 0.242)*, or an add-sign *(p = 0.941)* as obstruction methods. Using a tree as an obstruction method has a barely significant effect *(p = 0.046)*.
The advertisement on the add-sign has an impact on its effectivity. The add-sign displayed an advertisement of coffee. Qualitative analysis reveals that people that were fond of coffee were attracted to the sign instead of deterred from it. This is more apparent when the sign is placed on the right. Probably because the sign was more easily readable on the right-hand side.

The tree nudges people towards the opposite direction than initially expected. Qualitative analysis reveals that people were attracted to the tree since it was aesthetically pleasing and since it provided shadow. They thought that the presence of this tree would mean the path had more trees and found this appealing.
In general, these results show that obstruction methods are ineffective in nudging cyclists route choice. There are too many different interpretations possible for these interventions. The effects that are found, lead in the opposite direction. Proving that aesthetics and expected comfort are more important to cyclist route choice than vision on the intersection.

3.2. Impact of hierarchy

Hierarchy involves creating a hierarchical road structure by placing road markings. Participants are hypothesised to prefer the main road. The three variants include: colouring the road, placing a white curve on the road edge, and using truncations. The variants differ in the amount of guidance given respectively. Overall, it is found that this method is very effective.
Colouring the road to imply a hierarchical structure has an insignificant effect *(p = 0.112)*. A significant effect is found when implying a hierarchical structure with either a thin white curve on the edge of the road *(p = <0.001)*, and by adding truncations *(p = <0.001)*.
The curve and the truncations work equally well in both directions, but the road works better when nudging people to the left. Theory is inconclusive on why this is the case.
It is rather peculiar that colouring the road is not an effective nudging method, since this is the method that is mostly used in practice. It could be that the contrast of the road was not high enough and this hindered its effectiveness.
In general, the results show that hierarchy is an effective method of nudging cyclists. The results also reveal that the level of guidance influences the effectivity of the nudging method.

3.3. Impact of herding

Herding involves drawing street art on the front wall with creatures and objects moving in a certain direction. According to theory people are tempted to move in the same direction as the street art is pointing. The three different variants include drawing a cyclist, drawing a fish, and drawing a wave moving in a certain direction. The three methods differ in their level of abstraction respectively.
A significant effect is found for a drawing of a cyclist *(p = 0.002)*, a fish *(p = <0.001)*, and a wave *(p = <0,001)*.
The effect of a cyclist is similarly effective in both directions. The effect of the drawing of a fish is more effective to the right and the effect of the wave is even more skewed to the right.
This nudging method is bound in the theory of both herding and deflection. Deflection happens when people see something interesting but cannot see it fully. The drawings on the wall were cut off on the right, but not on the left. This means that deflection is stronger to the right whereas the effect of herding is similarly strong in both directions.
The more abstract the painting becomes, the more the results become skewed to the right. This suggests that herding is less strong on drawings which are less human like.

3.4. Impact of personal characteristics

Several personal characteristics were hypothesised to impact nudge compliance. The results show that no personal characteristic has a significant impact on cyclist nudge compliance.
It does not matter how much experience people have with VR or gaming in general. It does not matter what gender, age or height they are either. It also does not matter how often they cycle, since what age they started cycling or if cycling is a common means of transportation in their country of origin.

Table 5 Effects of characteristics on nudge compliance

Characteristic	Chi-Square (χ^2)	df	Significance (p)
Commonality	0.01	1	0.94
CycleFrequency	0.85	4	0.93
Gender	0.74	1	0.39
Height	38.25	37	0.41
Age	32.97	34	0.52
Centrality	0.47	1	0.83
GameExp	2.47	4	0.65
VRExp	1.21	4	0.88
KnowPurpose	1.55	1	0.21

It also does not matter if people are aware that they are being nudged. This falls in line with theory (Thaler, 2008).
Some of these effects like age and gender were theorised to have different interactions with the three different nudging methods, so even though these effects are not significant, they will still be checked for possible interaction effects.
In general, these results indicate that nudging route choice can be done universally and that demographics are not an important factor in determining nudge compliance.

3.5. Impact of directional bias

As discovered in previous research, people feel compelled to turn right more often (Beek, 2024). This directional bias has also been observed in this study.
For the whole dataset 56.6% choices were made to turn right. With a one sample T-test it can be derived whether this is significantly different from a 50/50. It is found that people turn to the right significantly more often *(T = 28.60, p = <0.001)*.
(Beek, 2024) and (Bitgood, 1995) theorise that this directional bias falls off when nudging is applied. This study finds that cyclists turn right 62.2% of the time if no

nudging is present compared to 55.5% when nudging is present. This difference is significant for a 90% confidence interval *($\chi^2 = 3.62, p = 0.057$)*. This study suggests that directional bias becomes weaker when nudging is present, but subsequent research should be performed to fully prove this.
Some characteristics were thought to influence directional bias. It is found that these effects all point in the opposite direction from what theory suggests. Having a dominant right eye for example, results in people going more to the left. None of these effects are significant, however the fact that they all point in the opposite direction from the line of theory merits further research. For this study directional bias is seen as a constant which is not influenced by any characteristics.

Table 6 Effect of characteristics on directional bias

Factor of influence	Percentage turning right (%) (Base = 56.6%)	Chi-Square (χ^2)	Significance (p)
DomEyeRight	55.4	2.28	0.131
DomEyeLeft	58.7	1.11	0.293
DomHandLeft	56.8	0.01	0.941
DriveOnRightSide	56.2	0.68	0.411

3.6. Impact of interaction effects

With an MNL model the interaction effects between characteristics and nudging methods are explored. Every characteristic has been added to the MNL model separately to see whether it has significant interactions with the three nudging methods.
It is found that two interactions are found to be significant. The interaction between cycle frequency and obstruction is significant *($T = -3.08, p = 0.002$)*. This means that people who cycle more often are significantly less affected by obstruction methods. This could be the case since less experienced cyclists are more considerate about their own safety (Kubat, 2020).
The other significant interaction is between hierarchy and whether people were trying to stay centred *($T = -3.08, p = 0.002$)*. This means that cyclists who are trying to stay centred react less on stripes on the road. These people are probably less affected by all three nudging methods, since they are busy with staying centred. The effect is more visible since hierarchy itself had the strongest effect.
The utility function has been updated to only include significant characteristics. The non-significant nudging methods have been included in the final model. This is done since their significance could have been changed by the other interaction variables and they themselves are important to the significance of the interaction variables.

Table 7 Model estimates

Variable	Estimate	T-Test	Significance
β_Bush	0.68	1.06	0.153
β_Tree	-1.18	-1.49	0.067
β_AddSign	-0.25	-0.41	0.355
β_RoadColour	0.38	1.50	0.074
β_Curve	1.30	4.30	<0.001
β_Truncation	1.54	4.42	<0.001
β_Bike	0.62	2.94	0.002
β_Fish	0.70	3.24	<0.001
β_Wave	0.74	3.43	<0.001
β_Cyclefrequency*Obstruction	-0.16	-3.08	0.002
β_Centrality*Hierarchy	-0.53	-3.01	0.002
β_0	0.28	4.32	<0.001

The full model has a final Loglikelihood of -698.56 (adj. $Rho^2 = 0.059$). Most significances stay the same, though two notable differences can be seen. The intervention using the tree has fallen to only being significant for a 90% confidence interval *($p = 0.067$)*. The road colour intervention rises to also being significant for a 90% confidence interval *($p = 0.074$)*.
These differences are caused by the addition of the directional bias *(β_0)*. This directional bias points to the right and slightly explains the effectivity of the tree. Since road colour is the only intervention method that works better to the right it receives a bump in significance due to the addition of *β_0*.

4. Conclusion and recommendations

The aim of this research is to explore how infrastructure can be used to nudge cyclists in favourable directions. A Virtual Reality (VR) experiment with a bicycle simulator was constructed and conducted to understand the impact of three different promising nudging methods on unsignalized, obstructing the view of one of the two directions, implying a hierarchical road structure with road markings, and abusing herding behaviour with wall art.
This study shows that cyclists are affected strongly by hierarchy and herding methods but are not affected by obstruction methods. Therefore, it can be concluded that nudging can be effective in influencing cyclist route choice. Moreover, this study found that the effectiveness of nudging methods is not influenced by personal characteristics such as age, gender, or height. This makes these nudging methods effective regardless of demographics. It does not matter if people are aware of them being nudged. This study has also found that cyclists have a directional bias to the right. This bias dissipates slightly when nudging is applied but does not disappear completely.

This study was performed in VR due to its controllability and low cost, however it is not fully sufficient in validating results due to its relatively lacking representability. It does not include effects like distance, familiarity, and other road users. The fact that people know they are in an experiment can influence their behaviour which can be detrimental to a study focussed on the subconscious. Therefore, it is recommended to perform a follow-up study with a field test to further validate the results.
The effect of eye- and hand dominance on directional bias could not be validated. The results are all insignificant, but they all point in the opposite direction from theory. Therefore, it is strongly suggested to perform more in-depth research into factors influencing directional bias.
Also, the results suggest that the strength of herding becomes weaker when the depicted drawings are less human like. It would be strongly recommended to perform research into herding and how abstraction can influence its effect.
Finally, the effect that colour, light and sound have on cyclist route choice have all not been studied yet. They were found to be too vast to include in this research but do merit research of their own.

Contribution statement

Aik van Seters: Writing, Methodology, Investigation, Conceptualisation, Experiment design, VR environment, Experiment conduction, Data analysis
Dorine Duives: Writing-Review, Conceptualisation, Supervision
Yan Feng: Writing-Review, VR environment-Review, Supervision
Maarten Kroesen: Writing-Review, Data analysis-Review, Supervision
Jacob Tielemans: Writing-Review, Experiment design-Review, Supervision

Data availability

Data will be made available on request.

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A2: VR Construction logbook

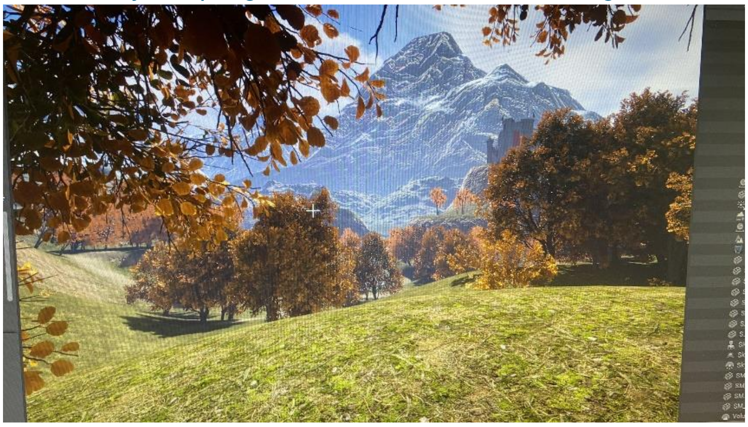
In this logbook the process of creating the VR environment will be described. First, an overview of all used software and hardware will be given, and then the process will be described week by week.

Overview of the used software and hardware

The experiment environment will be made in Unreal Engine 5.1. This engine is chosen because of three main reasons. First, it couples very well with Virtual reality. It has a lot of systems which make integrating VR in the environment effortless. Second, it is quite easy to learn. Compared to engines like Unity and coding it yourself, unreal engine is a very easy method of modelling an environment with a visual scripting language which makes integrating functionality quite easy as well. The final and most important reason of choosing this engine is the support it receives from the university. There is a whole team at the university who works fulltime with Unreal and can give support as needed.
Blender 3.6 will be used to make models as needed. The aim of this research is to convey a realistic Dutch street to the participants. To accomplish this some custom models must be made since they are not publicly available. Blender will be used instead of Maya since Blender is open source. The university team has had issues with the licensing of Maya, so Blender will be used to be safe, even though it is less qualified for making infrastructure models.
The VR headset that is used will be the Meta Quest 3, since this is the one available at the TU Delft and is also easy to use in tandem with Unreal.
A bicycle controller is already made for UE5.1. It connects to an actual bicycle using a raspberry pie. This way the participants can cycle on the bicycle and have their virtual bicycle react in real time. The system does not include the ability to turn the bicycle, so another method of doing this has to be developed.

Week 11: Getting used to Unreal

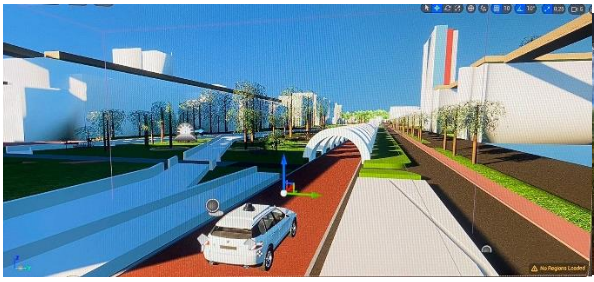
The first week was all about getting used to Unreal engine. I have never used the system before, so I took three days this week to get used to the program, its tools and its power. After 20 hours of tutorials, I was able to get a grasp of the navigation trough the menu's, The manipulation of objects, the visual scripting system and the material system. I ended the week by sculpting a luscious environment, using nanite to keep its performance very high.



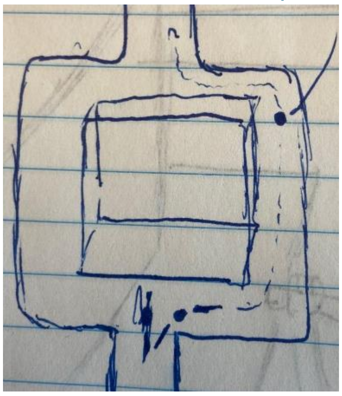
Happy with the results, I went into the next week.

Week 12: Learning about its limitations

The second week was a lot less optimistic then the first one. I learned about the importance of motion sickness and how important it is to limit this as much as possible. Also, I learned that both nanite and lumen, two systems to steeply increase fidelity whilst keeping processing power low, do not work in VR. Having high resolution models and textures would slow down the machine too much so were to be avoided. The environment would then look more like this then first envisioned.




I decided to mainly work on developing the story for my experiment. What would the environment look like and what decisions would the respondent have to make? I settled on the following design:



The cyclist would be asked to travel in a straight path and would be presented with a series of junctions. They would have to make the decision to go right or left and eventually meet up at the same location. At every junction the environment would be altered slightly to nudge them in a certain direction.

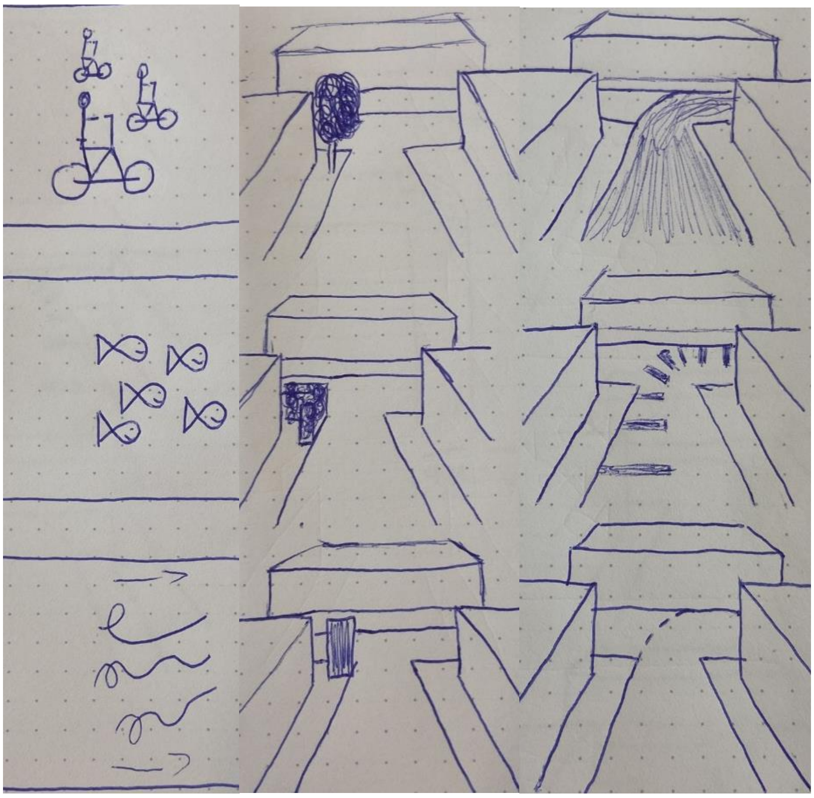
As you can see above The participants must make 4 turns every time they make a decision. Since they cannot turn the bicycle themselves, they will press a button and then go down the set path. This can result in them getting motion sick. To combat this, three methods have been considered and tested using a quick spline setup.

For the first method the camera would not turn in unison with the bicycle. The cyclist would have to look left themselves when the bicycle turns left. This way the negative effect of the turning is negated. It did not feel right though. Since you are sitting straight and must look ninety degrees to the left to see where the bike is going.

The second method involves the camera zooming out. When the bicycle was about to make the turning sequence, the camera would zoom out. The participant could look down on their bike and keep pedaling whilst it made its movements. This method was also not chosen because we were afraid it would break the immersion of non-experienced VR users.

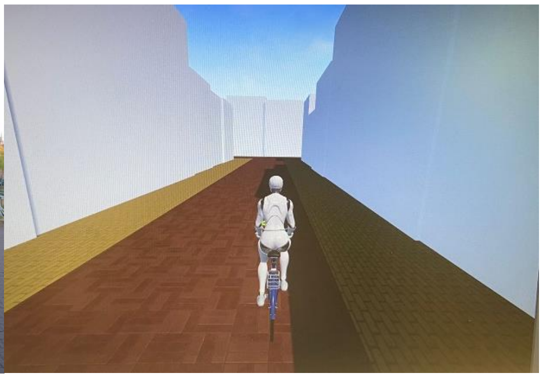
The final method is the one that was finally chosen. The participant would be on the bicycle whilst it is turning and turn with it, but the bike would turn very fast. In about 3 frames it turns 90 degrees. Slow enough for our eyes to notice, but too quick for our cardiovascular system to catch up. The people form the VRzone theorized that this way people would not get motion sick, but this still had to be tested.

Whilst doing this I was also busy in the office defining the interventions that are going to be used in the experiment. We settled on having 9 nudging methods. Together with two times the base situation this would lead to the participants having to make 11 decisions. It was hypothesized that the participants could make around 10 to 16 decisions before getting bored, so this fits that amount well. The chosen decisions are the following: The explanations behind this list can be found in the main report.



Week 13: Modelling in Unreal and Blender

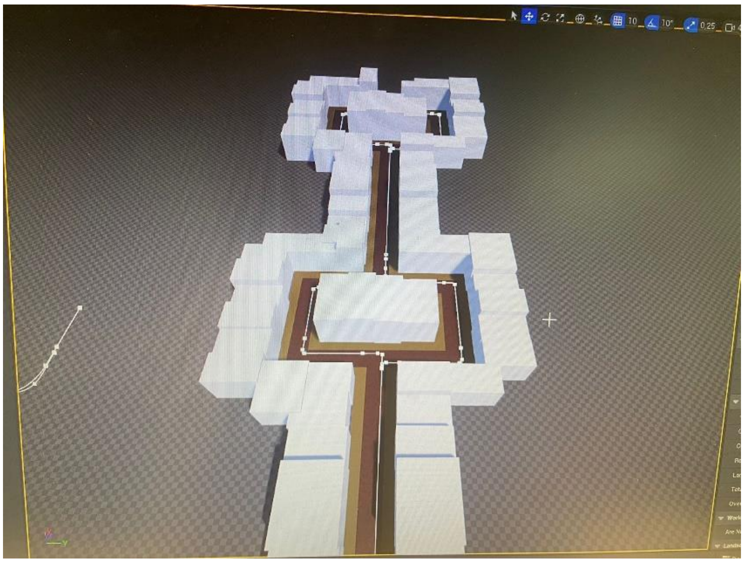
The third week was used to create a first version of the simulation. The street was designed in accordance with the official measurements required by the CROW. The road is based upon a street in which cars can only drive in one direction and cyclists can cycle in both directions. This makes the sidewalks 2,4 meters wide (it is 0,4 wider than necessary to account for the inclusion of trees) and the road 4,4 meters wide. The street itself is based on streets in the city center of Delft. With interlacing red bricks for the cars and cyclists and small elongated yellow bricks for the pedestrians.



The buildings are interlocking with random height and width offsets to make it feel like a Dutch neighbourhood. The buildings themselves will be improved upon later, by adding texture and windows.

After generating this a small detour was made to learn how to work with blender. After a day of work the pedestrian walkways with curbs were created, but after tha6t detour it was decided that it is better to first work on the functionality, since changing this could probably alter the appearance as well.

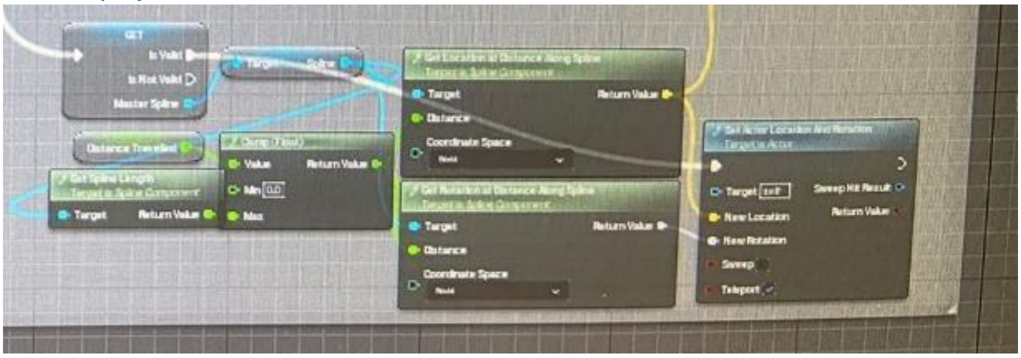
So, a simple spline system was created on which the cyclist can travel.



The cyclist moves along the white line in the middle of the road and follows the curves of this spline through the environment. A lot of was put into the speed of the turns, to make it feel like you are turning without making participants nauseous, though non experienced users were yet to test it.
The system could not make turns yet. It basically goes right every time through the environment.

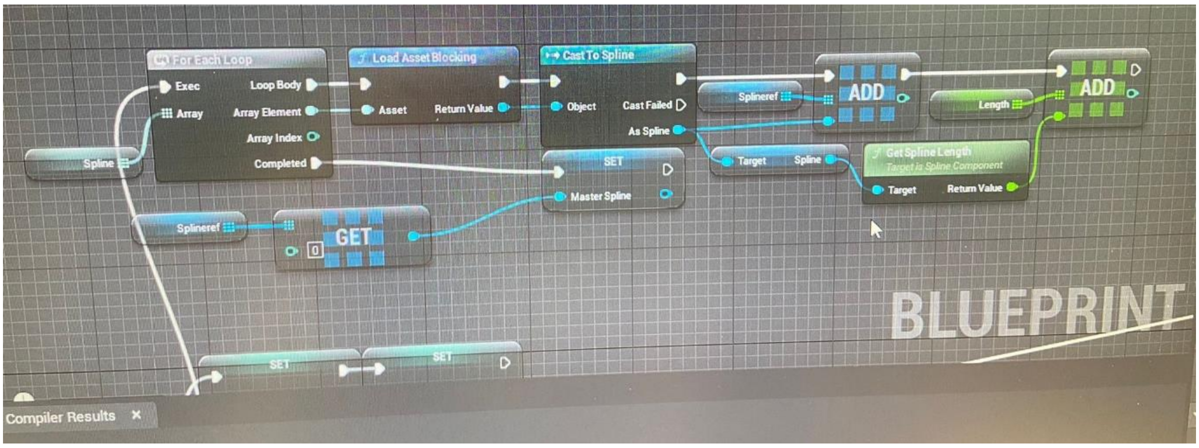
Week 14: Adding functionality

this week was all about adding the needed functionality to the system. A lot of work has gone into making the movement and picking directions work. It resulted in the largest block of code that will be added to the existing bicycle controller in this project. The code that is added to achieve this is explained below

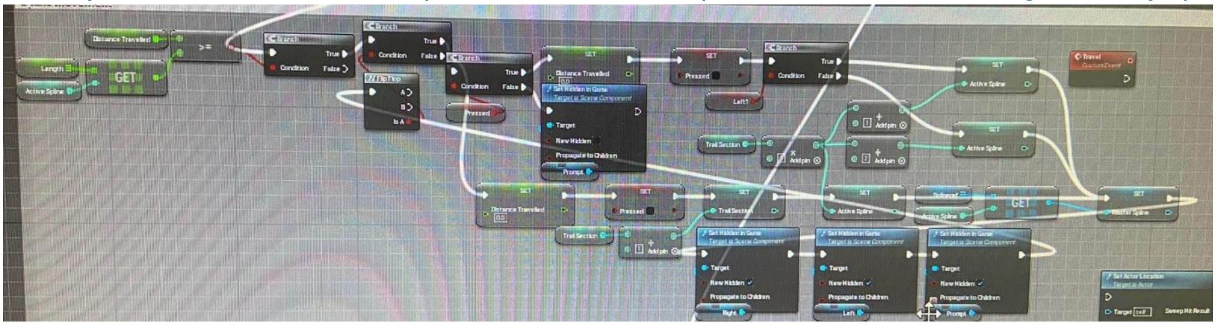


This is the code that controls the movement along the spline. The systems already calculated speed and distance. The distance value is copied to another variable (spline distance) and used here. It checks the length of the active spline (the master spline) and uses that to calculate the position the player should be along this spline. For that position it calculates the location and rotation of that spline. It sets the location and position of the player to that and does this every tick. This way the player moves smoothly along the spline.

To know what direction the player needs to go, this code is used. It has two buttons (left and right), which can be pressed. Whenever one of these buttons is pressed the Boolean (left?) is set to true or false. Also, an arrow is displayed on the handlebars of the player indication which way they have selected. Finally, the Boolean pressed is set to true, to be used later.



Before the most important code is explained this part should be explained first. This code is activated at the very start of the programn and loads in all splines. Basically every section has three splines. The first spline represents the lead up. The straight path that the player cyles on before making their choice. The next two represent the right path and the left path. The cyclists wil travel on one of these paths based on the choice they made, before entering the next section. There are 11 choices so 11 sections. This means that 33 splines have to loaded in. This code loads in all the splines in an array of size 33. It sets the first spline to be the master spline and calculates the length of every spline.



The biggest block of code starts on the top left. Every tick it is checked whether the spline distance is equal or larger than the active spline length. If this is the case the code runs. This code oscillates between two functionalities: moving from a straight path to a curve and the other way around.

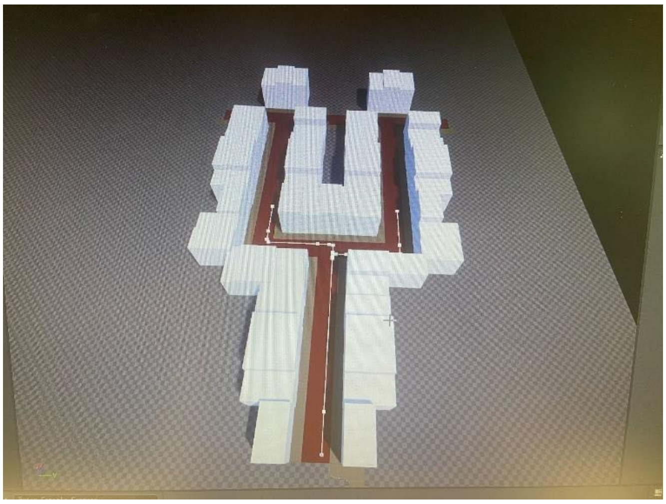
When the cyclist moves from a straight path to a curve the system first checks if a button is pressed so a choice is made. If not, it displays a text prompting the player to decide and waits until a choice is made. If a choice is made its first sets the pressed condition to false and then sets the spline distance to zero, so the player starts at the start of the next spline. Then is selects this next spline. It checks whether the player is going right or left and does some basic logic based on that. It makes the active spline equal to 3x the active section + 1 for left and 2 for right. Since every section is divided in three splines this logic checks out. Finally, it clears out all UI elements, being the arrows and decision prompt and goes back to checking the distance along the spline.

If the cyclist moves from the curve to a straight path the logic is easier. It does not have to check if a decision is made since it just has one option, so it starts by making the spline distance 0 and the pressed condition false. Then it bumps the active section integer up by one. Since every straight spline marks a new section. Then it sets the active spline equal to 3x the active section and clears all UI elements.

This method is easy and elegant and makes adding new road sections very easy. The experiment can easily be made bigger or smaller if needed. More possible directions could also be introduced in subsequent experiments. The code is designed in such a way that it is as adaptable as possible. It required some tweaking but switches between splines seamlessly.

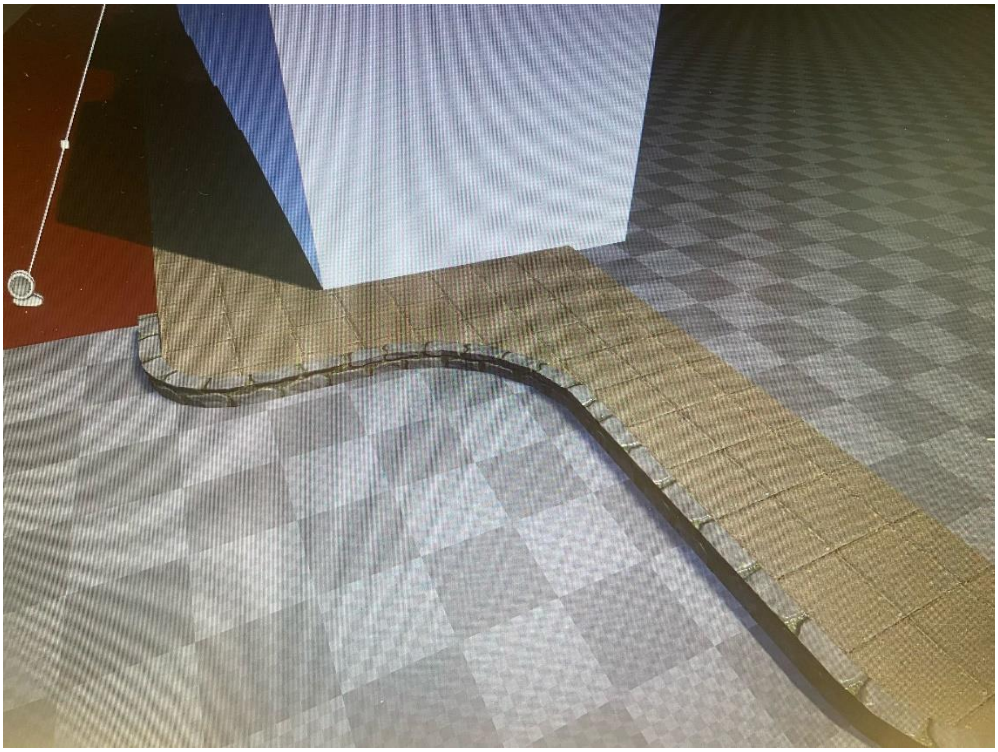
Week 15: Appearance alterations and first physical test

After consultation with my supervisors some changes had to be made to the environment.



First of all, the road layout has been changed slightly. Instead of going back to the middle, the road goes outwards and not back again. This is done to keep the amount of turns down as much as possible to reduce the risk of motion sickness. It could lead to some cognitive issues, since people will try to go as straight as possible, but if their destiny is made to be as wide as possible (EG. A river) this effect could be reduced. The option of only having one turn per decision was also explored, but it would lead to cognitive dissonance due to people trying to go as straight as possible.
To make this work properly the code has been remade to work differently. First, the splines have been limited to just be 3 splines. They get teleported to the right location every time the player moves over one. With the same system the environment also gets spawned in. Whenever the player goes on one of the splines with a turn, a new cross section is spawned in at the right location. This way the cyclists could in theory keep moving through the environment infinitely. Every cross section has been converted into blueprints to make this possible. In a later stage of development, the unnecessary cross section will be removed to spare processing power. We want to keep the environment so small as possible so maximum detail can be achieved whilst keeping performance optimal.

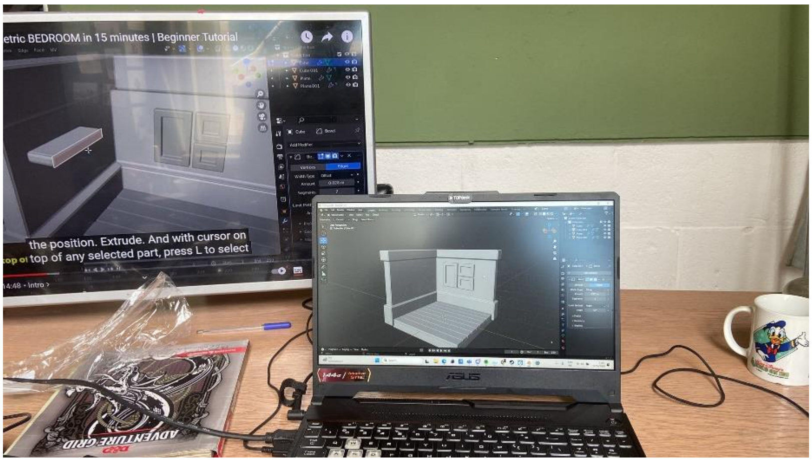
Secondly the road profile has been changed slightly as well. The road felt a little bit claustrophobic and narrow, so it has been changed to the profile of a two-way car street, being a width of 5,8 meters. Also, the pedestrian walkways have been changed to being classic 30cm tiles. These tiles represent a little more of a suburban area, rather than the inner-city center.
When this was done I started to work on the first models in blender for the project.



Three separate models for the sidewalk have been created and UVmapped: A straight one an inward curve and an outward curve. This will make it easy and not very heavy on the processor to make a sidewalk in the final product. The textures are also made in such a way that they are easily adaptable in texture colour size and rotation. The straight sections have been made in such a way that they can be made longer without compromising the texture quality.
After this I started to work on the first house design in UE. But after a bit of work, I decided together with my supervisors that it would be better to make this in blender so I will leave this for next week and move on to more pressing matters.
The more pressing matters were about the bicycle setup. I have discussed the feasibility of moving the bicycle setup to Amersfoort and concluded that this will be doable. Also, I have used the bicycle VR system for the first time. It works but sadly not with my program yet. Apparently, I have to build the project in the VR zone before moving to the building with the experiment. Opening it in Unreal crashes the system. Next week I will test it for the first time with my own experiment.
Then, I wrote some code to make different intervention methods spawn. The system will work in the following way. Every instance a random environment will be spawned from 4 presets, with buildings in different location to reduce the repetitiveness of the experiment. Then the intervention method will be spawned on top. For now, a rough first version of the code was developed so the first intervention method could be constructed and tested. The first tested intervention method was the tree. I have tested all kinds of different trees, but finally stuck with a maple tree, because its leaves were the densest and quite low. Also, it fit in well with the environment. I locked the LOD to be at its maximum value, since it is important that it looks correct from the first moment it is seen. This will not be done for the other trees in the environment to spare the CPU. Maybe a form of dynamic LOD will be used later where the trees get to a higher LOD sooner, but this is to be decided upon later.
Finally, I had my first physical test person try the environment. He said the turns feel not very distracting, the cycling feels good and the turning with buttons (or in this case voice signals to me) were fitting. He also did not get very motion sick, even though this was his first time using the VR system. I assume that he went easy on me and there are definitely some flaws in my design, but for now it is nice to see that no major errors are detected, and I will continue having physical tests every week from now on.

Week 16: Level building and building modeling

At the start of this week, I designed the level layout. The infinite road generation algorithm was updated to support the 11 intersections in the experiment. Also, the ability to remove earlier road segments was added. This way only 2 sections are loaded at any one time, aiding in performance. Especially since lumen must be used for the lighting, keeping down the number of elements can be very useful.
Next up, the actual intervention elements were implemented in the road sections. A model has been made for the elements shown on the road. The tree was pulled from existing elements. The hedge was made with two blocks and a grass texture and for the other 4 intervention methods placeholder elements were used.
The next day, some basic blender tutorials were followed to prepare for the house modelling process.



The day after, six different houses were modeled in blender. The textures used on these building was programmed in such a way that the brick and wood colour can be tweaked per instance. The building can also be mirrored. This way a few buildings can create a plethora of different combinations and quite realistically represent a Dutch neighbourhood.

Week 17: Building the neighborhoods and own project physical test

At the start of this week the buildings made in last week were arranged to make neighborhoods. 3 base scenarios were built and coloured. Then these base scenarios were copy pasted and mirrored where necessary to be the backdrop for the actual road sections. For every individual level the doors were also coloured in several colours to make them more distinct. Some street lanterns were also modeled to be added to the street view.

The buildings look quite barren and unlived. I have tried for some time to simulate the inside of these buildings using parallax occlusion, but this proved to be too extensive for my project. Due to the lack of curtain textures online a backdrop of chrome was chosen, since it looks like the windows are merely clouded and therefore not see-through.

The environment then finally looks like this. After consultation with several people, it has been decided that this is a sufficient representation of the Dutch neighborhood. A few of the intervention methods can be seen above. Generally, the same base environment has been used and only the square with the intervention method has been changed. Most intervention methods are final, but the street art methods are all placeholders for now.
Next up, I used the enhanced input system of unreal to map the directions to the VR controllers. I built the project and tested it physically for the first time.
After the physical test it has been concluded that the turns in the system are too harsh. A new method of decreasing motion sickness will be used, namely decreasing FOV.

Week 18: FOV introduction and more testing

This week was spent mostly on revamping the movement system and introducing FOV reduction at the turns. The snap turning was removed since it was too harsh and worked disorienting. Since mellow turns can induce motion sickness another method of reducing this was introduced.
At every turn the system will now introduce a Vignette. This vignette will reduce the vision from 96 degrees to 60 degrees. This way the environment is observed as moving less fast, therefore reducing motion sickness. This new system also has the added benefit of being less disorienting to the participants. In the previous system people did not always expect the quick turning. Therefore the direction they were looking did not match where they wanted to look. In this new system this problem has been resolved by turning more mellowly and giving participants the time to react.
After implementing the vignette system, a tutorial environment was created. In this environment the controls are explained, and the participant gets time to get used to the environment for as long as they deem necessary.
After some more physical tests it can be concluded that this new environment induces less motion sickness that the previous one. People still get a bit motion sick, but the short duration compensates for this.

Week 19: Decision logger and polishing

At the start of this week a logger was constructed. The program now records all decisions that a person made and the time they made them in a CSV. This process took around two days since unreal usually includes this functionality. A plugin had to be created and adapted to accommodate this functionality.
After the logger was constructed and finetuned an ending sequence was created. At the end the participants now arrive at the river, with a caption telling them the experiment is over and they may take off their headset.
Next the environments were polished up. Some glitched textures and holes in the environment were located and remedied.
Finally some street art for the herding intervention methods was created using Krita, a free to use open source photo editing program with which I was already familiar.

Week 20: Cleaning up the code and Midterm meeting

This week was all about finalizing the environment. Some minor bugs were fixed, and the code was made more readable.

Code explanation

In this chapter all code in the project will be explained.

The code is separated in 9 sections. Every section will be explained individually. It is important to note the greater functionality of this system.
The program works with spline-based movement. Which means that the bike follows an invisible line placed in the environment. Every map section is made in a separate blueprint, which can be found in the sections map in the unreal environment. Whenever parts of the experiment need to be swapped out, just these sections must be edited.

Events begin play

Whenever the experiment gets started the begin play event will get triggered. When this gets triggered 7 functions will be put in motion:
The first function increments the user ID. It checks how many experiments have already been performed and sets the ID of this experiment to one greater.
The first function loads in the spline elements. The bicycle will move along spline elements, these splines are defined in the experiment environment, but will be linked in this function. It also stores the length of each spline, which will be used later.
The second function sets all variables to the needed positions and loads in the first environment.
The third function Hides UI elements which should not be seen at the start of the experiment.
The fourth function prepares the VR environment, by putting the camera in the correct location and initializing the controller controls.
The last two function initialize the raspberry pie that will be used to record bicycle movement. This code is not made by me but by the VR zone Team. Therefore, I will not explain it in detail. The BindRedisCallback section is also part of this function.

Clear tutorial

This function is called by pressing / on the keyboard. It resets the environment to be used after the tutorial is deemed to be finished. This is done by clearing all variables that were used for the tutorial and loading in the new splines for the main experiment.

Movement controls

This function allows the bike to move right or left. By pressing the trigger on the controller, the corresponding Left? Variable is set to true or false. UI elements are swapped to give feedback to the participant on the direction they are heading. If the experiment is not in the tutorial anymore it will also log the decisions that were made with the log decision function

Log Data

This section handles the logging of the data. It has two functions.
The first function is the log decision function. It appends the decision made to a list. The decision will be describing the following elements in this exact order: The UserID, the Trial Section, The distance from the intersection, The decision to go right or left, and whether the environment is in its flipped state or not.
The second function adds the logged decisions to a CSV file. It is called whenever the experiment end is triggered.

Event Tick

This section is triggered every tick (around 60 times a second). It updates the distance traveled based on the current speed of the bicycle and then activates three functions which will all be explained in separate sections. These functions are. AddVignette, MoveTargetAlongSpline and SwitchActiveSpline.

Add Vignette

Add vignette adds a vignette to the screen. At the start of the turns it gradually cranks up the Vignette and at the end cranks it down again to lower the probability of motion sickness.

Move target along spline

This function handles the movement of the player along the spline. Every tick it takes the current distance and looks where on the spline this is and what rotation the spline has at this location. Then it teleports the player to this location and rotation. By doing this 60 times a second it creates smooth movement.

Switch spline

Switch spline is the most complicated function and is divided into several subfunctions. These functions will be explained on the order that they occur.

SwitchActiveSpline

Switchactivespline is the main body of the function. Every tick it checks whether the bike is at the end of the current spline. If this is the case, it checks whether it is at the end of the experiment. If so, it ends the experiment but if this is not the case it checks whether it is currently on a straight path or on a curve. If it is on a straight path, it starts the function to go to a curve and vice versa.

Move to straight path

This function moves the player from a curve to a straight path. It first sets the distance to 0. This way the player will start at the start of the next spline. It then sets the next active spline equal to 0, which is the index of the straight path. Then it uses the move spline function to move the curve tracts to the end of the straight track, therefore allowing the cyclist to change splines again when it reaches the end. Finally, it sets the active spline to the master spline. So, the bike switches to the new track.

Move To Curve

This function moves the player from a straight path to a curve. It is like the previous function but has some added functionality. First it checks whether the player has made a decision. If not, it waits until the player does. Leaving the bike standing still until a decision is made. Then it increments the section number so the next section will be loaded. It sets the active spline to 1 or 2 based on the direction the player chose. It moves the straight path to the end of the chosen curved path and loads in a new level element being the tutorial or experiment environment. Finally, it destroys past elements so only 2 sections are loaded at the same time. Then it once again sets the active spline to the master spline.

MoveSpline

This function moves the splines forward so infinite movement is created with only 3 elements. It checks the location of the active spline and moves the previous spline to the end of the active spline.

LoadNextSection

This function loads in the level environment. It checks the end location of the current active spline and spawns a new section in that location. The section that it spawns is based on the current trial section. There is a list of all 14 sections in order. Based on the current trial section this function chooses the correct environment and spawns it in, also keeping in mind whether the environment is mirrored or not.

LoadTutorialSection

This function is a simplified version of the previous function, that only loads the tutorial environment.

Shutdown sequence

This section ends the experiment when necessary. When the final location is reached EndSequence is called. This function tells the participant that they can take of their headset and logs the collected data.
The shutdownsequence is called whenever the operator presses escape. It shuts down all elements and closes the application.

A3: Survey questions

Questionnaire bicycle research

This is a short questionnaire following the experiment you have just done. It is split in three parts. The first part is mandatory, since it will be linked directly to the experiment in order to get results. The other two parts are more generally about the VR environment and are both non-mandatory. If you do not have the time you can skip these, however it would still be very much appreciated if you would also fill in the other two questionnaires.

* Required

Main questionnaire

This part is the main questionnaire. All the answers given will be strictly confidential and anonymous.

What is your pairing Code? (As given by the operator) *

What is your age? *

What is your gender? *

- ◯ Prefer not to say
- ◯ Woman
- ◯ Man
- ◯ Other

What is your height? (cm) *

Are you left or right handed? *

- ◯ Left
- ◯ Right
- ◯ Both

What is your dominant eye?
You can check this in the following way:
- Put your index finger close to your face in front of you and look at it with both your eyes
- Close one of your eyes. Does the location of your finger change?
- If it does, the eye you closed is your dominant eye. *

◯ Left

◯ Right

◯ I don't know

Do you have any sight or balance issues? (If not leave this empty)

[ ]

What age were you when you started riding a bicycle? (best guess) *

[ ]

How often do you ride a bicycle? *

Almost every day	Three times a week or more	Once/twice a week	less then once a week	Almost never
◯	◯	◯	◯	◯

Is cycling a common way of transportation in your country of origin? *

◯ Yes

◯ No

Do you drive on the right or the left hand side of the road in your country of origin? *

◯ Left

◯ Right

How experienced are you with video games *

1	2	3	4	5
I have never played a video game in my life				I play video games (almost) every day

How experienced are you with Virtual Reality *

1	2	3	4	5

This is the first time experiencing it — I use it (at least) once a week

Did you feel like you made the decision to go in a direction to stay centered? (EG Last three times you went right so now you go left) *

- yes
- No

What do you think is the topic of this research? *

Is there anything notable you want to share? *

Presence questionnaire

This part of the questionnaire will go in depth about the environment. How did it feel, did you feel like your choices mattered? etc. Every question is to be answered on a scale of 1 to 7. If you do not have time to answer this section you can skip it on the bottom of the page.

1 = Very poorly
2 = Poorly
3 = Below average
4 = Average
5 = Above average
6 = Good
7 = Excellent

How much were you able to control events?

1	2	3	4	5	6	7

How responsive was the environment to actions that you initiated (or performed)

1	2	3	4	5	6	7

How natural did your interactions with the environment seem?

1	2	3	4	5	6	7

How much did the visual aspects of the environment involve you?

1	2	3	4	5	6	7

How much did the auditory aspects of the environment involve you?

1	2	3	4	5	6	7

How natural was the mechanism which controlled movement through the environment?

1	2	3	4	5	6	7

How compelling was your sense of objects moving through space?

1	2	3	4	5	6	7

How much did your experience in the virtual environment seem consistent with your real-world experience ?

1	2	3	4	5	6	7

Were you able to anticipate what would happen next in response to the actions that you performed?

1	2	3	4	5	6	7

How completely were you able to actively survey or search the environment using vision?

1	2	3	4	5	6	7

How well could you identify sounds?

1	2	3	4	5	6	7

How well could you localize sounds?

1	2	3	4	5	6	7

How much were you able to actively survey or search the environment using touch?

1	2	3	4	5	6	7

How compelling was your sense of moving around inside the virtual environment?

1	2	3	4	5	6	7

How closely were you able to examine objects?

1	2	3	4	5	6	7

How well could you examine objects from multiple viewpoints?

1	2	3	4	5	6	7

How well could you move or manipulate objects in the virtual environment?

1	2	3	4	5	6	7

How involved were you in the virtual environment experience?

1	2	3	4	5	6	7

How did you experience delay between your actions and expected outcomes?

1	2	3	4	5	6	7

How quickly did you adjust to the virtual environment experience?

1	2	3	4	5	6	7

How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

1	2	3	4	5	6	7

How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

1	2	3	4	5	6	7

How much did the control devices interfere with the performance of assigned tasks or with other activities?

1	2	3	4	5	6	7

How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

1	2	3	4	5	6	7

How completely were your senses engaged in this experience?

1	2	3	4	5	6	7

Were there moments during the virtual environment experience when you felt completely focused on the task or environment?

1	2	3	4	5	6	7

How easily did you adjust to the control devices used to interact with the virtual environment?

1	2	3	4	5	6	7

Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?

1	2	3	4	5	6	7

Usability scale

This part of the questionnaire will more specifically go into the quality of the VR hardware. Is it easy to use and are there things to be improved? If you do not have time to answer this section you can skip it on the bottom of the page.

Usability scale

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree (5)
I think that I would like to use this system frequently	○	○	○	○	○
I found the system unnecessarily complex	○	○	○	○	○
I thought the system was easy to use	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system	○	○	○	○	○
I found the various functions in this system were well integrated	○	○	○	○	○
I thought there was too much inconsistency in this system	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly	○	○	○	○	○
I found the system very cumbersome to use	○	○	○	○	○
I felt very confident using the system	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system	○	○	○	○	○

A4: Consent form

Opening statement – Virtual reality (VR) Experiment
You are being invited to participate in a research study funded by Netherlands Organisation for Scientific Research (NWO). It is performed by Aik van Seters from the department of Transport Infrastructure & logistics at the TU Delft. The purpose of this research is to enhance our scientific understanding related to cyclist behaviour. The experiment will take you approximately 20 minutes to complete including the post-experiment questionnaire.
The experiment consists of two phases including one virtual reality (VR) experiment and an additional questionnaire. In the VR experiment you will need to travel to the river through an urban environment using a HTC Vive head-mounted display VR system. You will control the propulsion of the bicycle by pedalling an actual bicycle, but the turning will be done by pressing buttons on the handlebars. Please be aware that the experiment uses snap turning. This can be disorienting at first, but is done to reduce motion sickness. After the experiment you will be asked to fill in the post-experiment questionnaire on the laptop.
As with any online activity and online data storage, the risk of a breach or hack is not fully suppressed. Your personal data including the data from the informed consent form, the experiment and the post-experiment questionnaire will remain confidential to the best of our ability. We will minimize any risks by storing data securely on an encrypted laptop with an up-to-date RHDHV security system. Moreover, we will delete all personal data (e.g., name, email address and telephone number) from our datasets as soon as possible, which is no later than the end of the set of experiments on June 20th, 2024. Please be informed that the data of every participant is anonymous, before it will be used for publication purposes.
Your participation in this study is entirely voluntary and you can withdraw at any time before and during the experiment without any repercussions, i.e. you are still eligible for the voucher. You are free to omit questions and are able to withdraw your participation until the data is fully anonymized.

The experiment is approved by the Human Research Ethic Committee (HREC) of the Delft University of Technology (Reference ID 2987).

INFORMED CONSENT

Name ……………………………………………

Location CEG Faculty Building, TU Delft / RHDHV headquarters, Amersfoort

Date ……………………………………………

Signature ……………………………………………

CHECKLIST

Please check the appropriate boxes	YES	NO
1) I have read the instruction document provided by the instructor regarding the experiment		
2) I understand that I can quit this experiment at any given moment without any repercussions		
3) I understand that I might suffer slight inconvenience from the VR headset. If this is the case, please notify us and we will stop the experiment directly		
4) I understand that I might suffer slight inconveniences in terms of motion sickness due to my immersion in the virtual environment. If this is the case, please notify us and we will stop the experiment directly		
5) I understand that the instructor nor TU Delft are not liable for any damage to your person sustained while moving and cycling through the virtual environment		
6) I understand that my personal data (name, email address and telephone number) is only used for the purpose of this experiment. They will be destroyed after the experiment has finished		
7) I understand that after the deletion of my personal data, it might become difficult for the researchers to erase my experimental data, as they might not be able to identify your records in the full dataset anymore		
8) I understand that the data gathered during this experiment will be made available for 3rd party research by other universities via the 4TU.network in an anonymous way (excl. videos and dates of the experiment)		
9) I understand that I am not allowed to participate with this experiment when I experience COVID-19 related symptoms (e.g., coughing, fever and runny nose)		

A5: Data formatting code

A6: Rstudio code

```r
# MNL model, route choice data
# SEN1721 - 2023
# Written by Jose Ignacio Hernandez

#######################################
#### Step 1: Load modules and data ####
#######################################

# Clear memory
rm(list = ls())

# Load Apollo library
library(apollo)

# Initialise code
apollo_initialise()

# Set core controls
apollo_control = list(
  modelName       = "MNL_ex1",
  modelDescr      = "MNL model for route choice data",
  indivID         = "Code",
  outputDirectory = "output",
  maxIterations = 300,
  panelData = FALSE
)

# Load data
database = read.csv('Formatted_data.csv',sep = ',',header = TRUE)

# Sort ID column
database = database[order(database[['Code']]),]

#######################################
###### Step 2: Define parameters ######
#######################################

# Define parameters
apollo_beta = c(
  b_bu = 0,
  b_ro = 0,
  b_bi = 0,
  b_cu = 0,
  b_tr = 0,
  b_wa = 0,
  b_ad = 0,
  b_fi = 0,
  b_tu = 0,
  b_0 = 0,
  b_fo = 0,
  b_chi = 0
  )

# Set fixed parameters. If no parameter is fixed, do not fill it
apollo_fixed = c()

# Validate inputs
apollo_inputs = apollo_validateInputs()
```

```
#########################################
##### Step 3: Define the MNL model ####
#########################################

apollo_probabilities=function(apollo_beta, apollo_inputs, functionality="estimate"){

  ### Attach inputs and detach after function exit
  apollo_attach(apollo_beta, apollo_inputs)
  on.exit(apollo_detach(apollo_beta, apollo_inputs))

  ### Create list of probabilities P
  P = list()

  ### List of utilities: these must use the same names as in mnl_settings, order is irrelevant
  V = list()
  V[["Left"]]  = NudgeLeft*((b_ad*Add+b_tr*Tree+b_bu*Bush) * (1 + b_fo * CycleFreq)
                            +(b_ro*Road+b_cu*Curve+b_tu*Trunc) * (1 + b_chi * Centrality)
                            +(b_bi*Bike+b_wa*Wave+b_fi*Fish))
  V[["Right"]] = b_0 + NudgeRight*((b_ad*Add+b_tr*Tree+b_bu*Bush) * (1 + b_fo * CycleFreq)
                                   +(b_ro*Road+b_cu*Curve+b_tu*Trunc) * (1 + b_chi * Centrality)
                                   +(b_bi*Bike+b_wa*Wave+b_fi*Fish))

  ### Define settings for MNL model component
  mnl_settings = list(
    alternatives  = c(Left=1, Right=0),
    avail         = list(Left=1, Right=1),
    choiceVar     = chose_left,
    utilities     = V
  )

  ### Compute probabilities using MNL model
  P[["model"]] = apollo_mnl(mnl_settings, functionality)

  ### Prepare and return outputs of function
  P = apollo_prepareProb(P, apollo_inputs, functionality)
  return(P)
}
#######################################
## Step 4: Estimate and print output ##
#######################################

# Estimate
model = apollo_estimate(apollo_beta, apollo_fixed, apollo_probabilities, apollo_inputs, estimate_settings=list (maxIterations=300))

# Print output
apollo_modelOutput(model)

# Save output
apollo_saveOutput(model)
```