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How do design aspects influence the attractiveness of cycling streetscapes: Results of virtual reality experiments in the Netherlands

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ABSTRACT

Understanding the determinants of cycling and thus creating optimal cycling conditions is still a challenge. The current study addresses this challenge by providing in-depth exploration of attributes of bicycle infrastructure, traffic volume, gradients, urbanisation degrees in stimulating cycling for various population categories. Participants had to cycle in a simulated VR environment mirroring the streetscape of a real Dutch city. The cognitive (e.g., safety perception) and affective (e.g., enjoyment, attractiveness) response was measured, real time.

The results suggest that various attributes impact the cognitive and affective components to different extents. In particular, bicycle path presence and intersection absence had a positive impact on safety perception. Greenness of the environment contributed for lifting the attractiveness of the cycling experience. Hight car traffic had a negative impact on the way safety, enjoyment and attractiveness of cycling was perceived. Current outcomes should be implemented in creating bicycle infrastructure that appropriately meets the demand for attractive cycling experience that is safe and enjoyable for all.

1. Introduction

Over the past decade, there has been an increased interest in stimulating cycling as a transport mode in Western cities (Gao et al., 2019; Mertens et al., 2016; Oakila et al., 2016; Pucher, & Buehler, 2008). Efforts in stimulating cycling are shared by transport researchers, policy makers and governments. For example, the mayor of Paris, Anne Hidalgo, has put the Plan Vélo central to her re-election program to transform Paris into a cycling friendly city. Cycling is regarded as a transport mode that is non-polluting, not contributing to congestion and is healthy because of the associated physical activities (Gao et al., 2017). Recently, to avoid the risk of contamination by the COVID-19 virus, citizens are encouraged to increase the use of cycling.

The increased interest in how to stimulate cycling has evoked a host of studies that have investigated different built environment factors, in order to inform planners to create favourable cycling conditions. Factors that repeatedly emerge from the literature as stimulating cycling (experience) include: cycling infrastructure (Fishman, Washington, & Haworth, 2012; Winters, Davidson, Kao, & Teschke, 2011), aesthetics (Fraser & Lock, 2010; Zlot & Schmid, 2005), land use (Cervero & Duncan, 2003; Larsen et al., 2009; Liu

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et al., 2020; Pucher & Buehler, 2008) and urban design (Gao et al., 2017; Mertens et al., 2016). Note however, implementing environmental interventions like infrastructure (e.g., Heinen et al., 2010; Lugo, 2013) is difficult, time and effort consuming as recognised by previous literature and urban design practices. Moreover, while some factors (e.g., density, built-up area) can be objectively defined and measured, experiences with these and other factors (e.g., aesthetics) are much more difficult to define and to measure, and thus calling to underpin subjective evaluations of objective design elements of cycling environments.

The present study addresses this methodological gap by employing immersive Virtual Reality (VR) environments in which respondents cycle mirroring a real bike ride. VR provides advantages being able to control variables of interest and to standardise representations of various factors (i.e. aesthetics, built-up areas) which are difficult to manipulate in a real life experimentation.

Usually, respondents in stated preference studies get verbal descriptions or still images of alternative environments presented to them. However, this approach relies heavily on the imagination of participants, possibly leading to error variance due to poor evaluability (Bateman, Day, Jones, & Jude, 2009; Farooq, Cherchi, & Sobhani, 2018; Verhoeven et al., 2017). The advantage of using VR is that it provides dynamic embodied interaction with the environment while being physically mobile. A comparative study with still images shows that VR gives a much better sense of being in the simulated world, in comparison to photographs (Birenboim et al., 2019).

Furthermore, highlighting the potential of VR in exploring cycling experience, it is important that various cognitive and affective components of cycling experiences are taken into account, such as safety, enjoyment and attractiveness (Bialkova, Ettema, & Dijst, 2018). In literature, however, a holistic understanding of these cycling experiences of objectively controlled environments based on systematic comparisons is lacking. This lacuna will be addressed in the current paper, developing a more detailed and systematic understanding of various cognitive and affective components of cycling experiences, such as safety, enjoyment and attractiveness. The main question we would like to answer based on virtual reality experiment is*: What is the impact of various environmental factors, including a) infrastructure, b) built-up area and aesthesis, c) traffic volume and pedestrians/cyclists flow, on both cognitive (*e.g.*, safety perception) and affective (*e.g.*, enjoyment, attractiveness) components of cycling experiences, real time?*

In present paper, we first present the theorical background inspiring the empirical research. After describing the methodology used, results are reported and discussed in line with the relevant theories. The paper will conclude highlighting crucial components in creating bicycle environments that appropriately meet the demand for attractive cycling experience, that is safe and enjoyable.

2. Background literature

Several environmental factors (e.g., infrastructure, built-up areas, aesthetics, traffic volume, pedestrians and other cyclists on road) emerged from literature as crucial determinants of cycling experience evaluation. In the following we zoom-in into how these factors influence safety, enjoyment and attractiveness of cycling. While safety has been addressed by almost all of the papers exploring cycling experience, enjoyment and attractiveness experience invites further investigation.

2.1. Traffic volume, cyclists and pedestrians

Extensively studied, the traffic volume in terms of cars, trucks, and other motorised vehicles on cycling safety perceptions and use has been reported to have negative impact (Foster, Panter, & Wareham, 2011; Fraser & Lock, 2010; Winters et al., 2011; Pucher et al., 2010). One might argue that the threshold value for the categorisation of traffic volume shall be crucial in drawing any conclusions. Although different metrics for categorizing traffic volume, studies are univocal that the more intensive the traffic is, the less people are willing to cycle (Chataway et al., 2014; Pucher, et al., 2010; Vedel, Jacobsen, & Skov-Petersen, 2017). By contrast, when streets/routes are away from traffic, people are more motivated to cycle (Winters et al., 2011).

While car traffic volume impact has been widely investigated, literature is scarce concerning the role of other road users, namely pedestrians and other cyclists. Increased number of cyclists on the same road might increase the risk of collisions. The same is true for the probability of pedestrians using or crossing roads (Lawson et al., 2013). Note, also, that studies on risk perception of routes/intersections and their impact on cycling propensity mainly employed surveys to investigate the overall risk perception of a route (Lawson et al., 2013), or a comparison of a self-reported number of cycling trips (Fraser & Lock, 2010; Winters et al., 2011), and may therefore not adequately represent the actual relationship between perceived safety and cycling.

In this respect, a VR bike experience (mirroring a real bike ride) will provide a direct measure of the actual perception of the parameters under investigation (Bialkova et al., 2018; Birenboim et al., 2019), namely, in the current case, the effect of traffic volumes of cars, cyclists and pedestrians have on cycling experience. Taken that the core exploration hereby is on cognitive as well as affective response, we hypothesise:

H1. Low car traffic volume leads to safer, more enjoyable, and more attractive cycling experience.
H2. Low number of pedestrians/cyclists on road leads to safer, more enjoyable, and more attractive cycling experience.

2.2. Infrastructure

To increase safety and to minimise the probability of collisions between cyclists and other road users, creating a dedicated bike infrastructure (e.g., separate bike paths) was recognised as crucial, a while ago (Fishman et al., 2012; Fraser & Lock, 2010; Pucher & Buehler, 2008). Separating bicycle paths from motorised traffic by means of a hedge, in comparison with a curb or a marked line, is seen as the most preferred infrastructure (Mertens et al., 2016; Verhoeven et al., 2017).

We have to point out here that previous studies focus mainly on safety experiences of infrastructures. However, cycling experience also includes other subjective experiences, such as enjoyment and attractiveness (Bialkova et al., 2018; Bialkova & Ettema, 2019). The authors have been able to show that factors influencing safety do not necessarily affect enjoyment and attractiveness to the same extent. Nevertheless, cognitive and affective evaluations have been found to form an overall construct of satisfaction with travel, as reported from travel satisfaction literature (Ettema et al., 2010, Friman et al., 2017). To disentangle whether and how various infrastructure factors influence enjoyment and attractiveness of cycling further investigation is needed. Therefore, we look at the cognitive and affective response, and predict:

H3. Safe cycling experience when a separate bicycle path is present, and when intersection is absent.
H4. Enjoyable and attractive cycling when bicycle path is present, and when intersection is absent.

We include intersection, as being part of infrastructure design, but also because the literature is scarce concerning exploration of cycling experience at cross points. While separate bicycle paths could increase safety when cycling, we assume that safety could be impaired at cross points. Our assumption is based on the fact that collisions between cyclists and motor vehicles (and/or pedestrians) are very likely to happen at intersections (Wang & Nihan, 2004). Not surprisingly then, cyclists reduce speed, and some even step off the bike at intersections in order to cross (Kircher et al., 2018). The risk of accidents can be reduced by appropriate design of junction crossings (Parkin, Wardman, & Page, 2007; Pucher & Buehler, 2008). Despite the recognised need of careful design of intersections (Kircher et al., 2018), prior studies reported a very limited influence of intersections on cycling levels (Lawson et al., 2013; Winters et al., 2011), and others did not find any relationship (Fraser & Lock, 2010).

2.3. Built-up environment and aesthetics

Despite the demand for evidences on whether and how urban landscapes determine bicycle travel (Cervero & Duncan, 2003; Ettema & Nieuwenhuis, 2017), the literature is not univocal on the effect built-up environment has on cycling (Fraser & Lock, 2010; Larsen et al., 2009; Lee & Moudon, 2008; Liu et al., 2020; Pucher & Buehler, 2008). Earlier research comparing cycling rates between neighborhoods has shown a positive impact of mixture of land uses, connectivity and design of cycling routes on cycling (Saelens, et al., 2003). Recent papers confirmed these prerequisite factors (Gao et al., 2018; Verhoeven et al., 2017). However, these studies are unclear about experiences of cycling. Note, that a large number of cycling trips does not necessarily mean that these trips are experienced as safe, enjoyable or attractive. It might be the case that people have to cycle due to the lack of other transport modes, e.g., in outskirts areas.

In addition to built-up environment attributes, factors like greenness, cleanness and aesthetics have been studied. By comparing self-reported number of cycling trips for various metropolitan areas differing in greenness (i.e. trees, vegetation), studies have shown a positive effect on cycling (Wendel-Vos et al., 2004; Zlot & Schmid, 2005; Mertens et al., 2016). It was also reported that the effect of vegetation was greatest when there was no bicycle path provided on the street, compared to all types of bicycle path (Mertens et al., 2016). Although the authors have not provided explanation on the underlying mechanisms, this is an interesting finding. It might be the case that environmental factors have a joint effect. Furthermore, we might expect that the joint effect of the environmental factors could influence various aspects of cycling (i.e. safety, enjoyment, attractiveness) in a different way. We therefore hypothesise:

H5. Cycling will be perceived being safer within green and clean environment.

Respectively,

H6. Cycling will be perceived as more enjoyable and attractive within green and clean environments.

We look at cleanness, as part of aesthetics. Explicit research on cleanness and its influence on cycling is scarce. A previous study, however, reported that cyclists might not be that sensitive to cleanness, and in particular, the effect size of cleanness perception depends on how physically active people are (Lee & Moudon, 2008). People who were more active physically, perceived cleanness to be important. Thus, one might argue that the profile of the cyclist will determine how the cycling is experienced. Whether this is the case, could be tested by looking at the sociodemographic characteristics.

2.4. Sociodemographics

Various sociodemographic factors, like gender, cycling frequency have indeed shown to shape highly differentiated cycling experiences. Individual characteristics influenced city-wide safety perception of cycling, as a function of infrastructure availability (Branion-Calles et al., 2019). In general, senior citizens demonstrated to have different cycling behaviour than other age groups (Gao et al., 2017; Gao et al., 2019). Men outnumbered women in active transport (Grudgings et al., 2018), and only in countries with bicycle friendly infrastructure the number of actively cycling male and female seems to be pretty equal (Garrard, Rose, & Lo, 2008). Under the assumption that perception of the cycling environment is an important determinant of cycling behavior, abovementioned reports lead to the conclusion that encompassing sociodemographic parameters is highly recommended in order to investigate cycling experiences, the perception and evaluation by various population categories.

The current study will therefore attune the experimental design in line with the above recommendations and will zoom-in into the

Panel A

Panel B

Fig. 1. Examples of screenshots (Left panel - scenario 1: No path, green, mixed area, high traffic volume, low pedestrians flow, intersection, clean; Right panel - scenario 4: Bicycle path, No green, residential area, high traffic volume, low pedestrians flow, No intersection, clean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Experimental setting.

factors hypothesised to be crucial in shaping highly differentiated cycling experience. In particular, we look at cognitive (i.e. safety) and affective (i.e. enjoyment, attractiveness) components. Only such a multifaceted view will provide in-depth understanding on the way various factors (e.g., infrastructure, traffic, built up area) influence cycling experience, its perception and evaluation.

3. Methodology

3.1. Stimuli and design

An immersive Virtual Reality (VR) environment was created, with C# and Unity3D game-engine environments by a third party, a professional VR developer studio. These environments were mimicking the streetscape of a real Dutch city (see Fig. 1, for screenshot examples, and Appendix Table A1 for details). For the purpose of the study, 8 streetscapes (experimental conditions) were designed, after full crossing of the experimental factors, namely, Bicycle path (present vs. absent), Environmental greenness (green vs. no green),

Table 1
Details on sociodemographic characteristics of the sample.

Indicator	Level	% distribution
VR experience	Yes	55.0
	No	45.0
Cycling experience	Yes	95.6
	No	4.4
Gender	Male	51.5
	Female	48.5
Age	18–19	1.5
	20–29	29.4
	30–39	23.5
	40–49	16.2
	50–59	22.1
	> 60	7.4
Education	Primary educationMAVO/VMBO	1.5
	(secondary/vocational)MBO	2.9
	(middle management & vocational)HAVO/VWO	7.4
	(higher education - basis)	10.3
	HBO (university of applied sciences)	26.5
	University, bachelor	8.8
	University, master/PhD	39.7
	Other	2.9
Household status	Single, without children living at home	41.2
	Single, with children living at home	1.5
	Couple, without children living at home	30.9
	Couple, with children living at homeLiving with parent	22.1
	(s)	4.4
Having kids (6 years old or younger)	0	91.2
	1	8.8
Work status	Working, fulltime (30 h per week or more	60.3
	Working, part time (<30 h per week)	16.2
	Not working, looking for a job	7.4
	Not working, not looking for a job	1.5
	Student	2.9
	Retired	2.9
	Housewife/househusband	1.5
	Other	7.4
Income	< € 1.000	11.8
	€ 1.000 - € 2.000	19.1
	€ 2.000 - € 3.000	20.6
	€ 3.000 - € 4.000	14.7
	€ 4.000 - € 5.000	8.8
	> € 5.000	11.8
	Prefer not to say	13.2
Car ownership	0	39.7
	1	48.5
	2	11.8
Bike ownership	Yes	95.6
	No	4.4

Built up area (residential vs. mixed), Car traffic (low vs. high), Pedestrians/cyclists flow (low vs. high), Intersection (present vs. absent), Cleanness (clean vs. dirty). Based on a conjoint trial experiment, the eight streetscapes were randomly assigned to participants (each participant saw only 4 out of 8 conditions). The conditions were presented in a random order and a counterbalanced manner across participants.

3.2. Procedure and settings

The study was conducted in the city hall of the municipality of Utrecht, in a quiet corner assuring that we have privacy and a quality experimental work. Participants were first introduced to the experiment and have completed a consent form agreeing to take part in the study. Then they were invited to comfortably sit on a standard Dutch bicycle that was affixed to an electromagnetic trainer (Elite RealAxiom Wired), see Fig. 2. Participants were wearing an Oculus Rift headset, and the bicycle trainer was connected to a computer. Participants could accelerate and brake in a natural way using the bicycle pedals, but not steer. Note that in our experiments, we only have made use of cycling tracks which go straight on (without making a turn, left or right, on a roundabout, or on a cross road).

To familiarise with the virtual environment and the task, a short practice session (300 m long cycling segment, the same for all participants) was run. Then participants experienced 4 experimental blocks (each about 2 min long). In each block, one of the experimental conditions was presented. The order of blocks was randomised in advance, so that the experimental conditions are counterbalanced across participants, and completing a full conjoint trial.

Table 2
Overview of the constructs used, measuring scales, and reliability.

Construct	Measuring scale	Reliability
Enjoyment	single item in VR, "I enjoyed cycling in this environment" (1 = "strongly disagree", 7 = "strongly agree")	Different from neutral $p < .0001$
Safety	single item in VR, "I felt safe cycling in this environment" (1 = "strongly disagree", 7 = "strongly agree")	Different from neutral $p < .0001$
Attractiveness	single item in VR, "I find this environment attractive" (1 = "strongly disagree", 7 = "strongly agree")	Different from neutral $p < .0001$
Liking	single item in survey, Bialkova & van Gisbergen (2017) "I would have liked the experience to continue" (1 = "strongly disagree", 5 = "strongly agree")	Different from neutral $p < .05$
Naturalness	4 items in survey; adapted from Lessiter et al., (2001) e.g., "The displayed environment seemed natural" (1 = "strongly disagree", 5 = "strongly agree")	Cronbach's $\alpha > 0.71$ Different from neutral $p < .0001$
Presence	4 items in survey; adapted from Lessiter et al., (2001) e.g., "I felt I was visiting the places in the displayed environment" (1 = "strongly disagree", 5 = "strongly agree")	Cronbach's $\alpha > 0.82$ Different from neutral $p < .0001$
Engagement	single item in survey; from Lessiter et al., (2001) e.g., "I felt involved in the displayed environment" (1 = "strongly disagree", 5 = "strongly agree")	Different from neutral $p < .0001$

At the end of each block, participants rated how much they enjoyed the cycling, how safe and how attractive the environment was. Rating was conducted within the virtual environment by moving the head and staring at the desired answer, on a 7-point Likert scale (1 ="strongly disagree", 7 = "strongly agree"). In order to avoid long exposure to VR, which may increase the chance of negative side effects (e.g., Birenboim et al., 2019), it was decided to limit the experiments to ~10 min.

After having cycled, participants had to complete a survey (printed version). First, the just experienced cycling segments had to be ranked, in order from the most attractive to the least attractive. Then the VR experience was evaluated by standardised scales in terms of Presence and Naturalness, and a single item addressed Engagement and Liking. Presence is defined in terms of subjective experience of being in one place or environment (McMahan2003; Witmer & Singer, 1998) and naturalness as the believability of the depiction of the environment (Freeman & Lessiter, 2001). For VR environments, engagement reflects the degree of involvement (Freeman & Lessiter, 2001; Steuer, 1992), and was found to have positive influence on liking of the VR experiences (Bialkova & van Gisbergen, 2017). Table 2 provides details on the items used and the reliability check (see also Appendix, Table A2).

In the last part of the survey, sociodemographics were addressed, e.g., age, gender, education, household number, previous experience with VR, cycling experience, as well as barriers, stimulators, satisfaction of cycling. After completing the survey, participants were debriefed and thanked for the participation. 5 vouchers (20 euros each) were raffled among the participants, at the end of the study.

3.3. Participants

70 participants (35 male; mean age 39 years old) took part in the study. Data from two participants were excluded from further analyses, as they provided for all VR scenarios (and questions) the same response.

For 27 of the participants this was the first VR experience. Only 3 of the participants reported that they do not have a bike, and 3 have never or almost never cycled. 38% had secondary education and 50% had higher education. 75 % of the participants were currently working, 9% were unemployed, 3% were students, and 3% were retired. 32% received up to 2000 Euro net per mount (per person in household), 36 % received between 2000 and 4000 Euros, and 21% received above 4000 Euros. Majority, 48% had one car, 12% had two cars in the household, and 40% did not have a car. Majority, 41% considered to be in very good health, 25% in good, and 27% in excellent health. See Table 1 for details on the statistics concerning the sociodemographic characteristics of the sample.

In real-world field experimentation, it is usually difficult to ask respondents to cycle on different routes in such a controlled way (due to the time and budget limit) as we offer within the VR environments created in this study. Namely, multiple observations from the same respondent allow the researcher to capture preference heterogeneity within individuals and between individuals. In this respect, the current study provides unique methodological opportunity, as described in detail in the analytical procedure and results section.

Table 3
Model Statistics for Safety.

Predictor	χ2	*p*- value	AIC	BIC
Model 1				
(Base model: AIC = 218.9, BIC = 391.0, R^2adj = 0.29)				
Path	16,38	0.012*	223,38	373,88
Greenness	0.81	0.992	207.81	358.31
Built up area	7.93	0.243	214.92	365.43
Car Traffic	24.91	0.0001****	231.90	382.41
Pedestrian Traffic	3.20	0.783	210.19	360.70
Intersection	13.67	0.034*	220.66	371.16
Cleanness	6.71	0.348	213.71	364.21
Model 2 (VR experience: AIC = 368.2, BIC = 561.7, R^2adj = 0.31)				
Path	16.33	0.012*	372.57	544.58
Greenness	0.81	0.992	357.05	529.06
Built up area	7.91	0.245	364.15	536.16
Car Traffic	24.66	0.0001****	380.89	552.91
Pedestrian Traffic	3.14	0.791	359.38	531.39
Intersection	13.59	0.034*	369.84	541.85
Cleanness	6.94	0.326	363.18	535.19
VR experience	5.46	0.487	361.69	533.70
Model 3 (VR experience, Cycling frequency: AIC = 460.4, BIC = 675.4, R^2adj = 0.35)				
Path	16.01	0.014*	464.43	657.93
Greenness	1.01	0.985	449.42	642.93
Built up area	8.35	0.213	456.77	650.28
Car Traffic	24.66	0.0001****	473.08	666.58
Pedestrian Traffic	3.08	0.799	451.49	645.00
Intersection	14.22	0.027*	462.64	656.15
Cleanness	6.50	0.369	454.92	648.43
VR experience	5.25	0.513	453.66	647.17
Cycling frequency	17.05	0.009**	465.46	658.97
Model 4 (VR experience, Cycling frequency, Gender: AIC = 618.1, BIC = 919.1, R^2adj = 0.41)				
Path	16.63	0.011*	622.71	902.22
Greenness	1.16	0.979	607.23	886.76
Built up area	8.27	0.219	614.35	893.86
Car Traffic	25.35	0.0001****	631.43	910.94
Pedestrian Traffic	2.78	0.836	608.86	888.37
Intersection	15.51	0.017*	621.59	901.11
Cleanness	6.85	0.335	612.93	892.44
VR experience	1.27	0.973	607.35	886.86
Cycling frequency	5.92	0.433	611.99	891.51
Gender	4.81	0.568	610.89	890.40
CyclFreq × Gender	5.94	0.430	612.02	891.53
VR × CyclFreq	5.91	0.433	611.99	891.50
VR × Gender	5.09	0.532	611.17	890.69

Note: R^2adj-Nagelkerke, Akaike information criterion (AIC), Bayes information criterion (BIC).
Significance: *p <.05. **p <.01. ***p <.001. ****p <.0001.

4. Analytical procedure & results

4.1. VR experience evaluation

First, a standard reliability check was performed. The scales used were reliable, respectively, for Naturalness (Cronbach's $\alpha > 0.71$), and for Presence (Cronbach's $\alpha > 0.82$). T-tests were conducted to probe whether the evaluation is significantly different from neutral. The results confirmed that all dependent variables are significantly different from neutral (see Table 2 for details).

T-tests were performed to explore whether gender (male vs. female), previous VR experience (yes vs. no), and Bike ownership (yes vs. no) influenced naturalness and presence evaluation. ANOVAs tested whether naturalness and presence evaluation is influenced by cycling frequency (1 = Almost every day, 2 = At least once a week, 3 = Few times a month, 4 = Less than once a month, 5 = I never or almost never cycle).

Note that 55% of the respondents have experienced VR before, and 52% were male. Thus, we heave a well-balanced sample concerning these two parameters, i.e. previous VR experience and gender. One might argue that 55% previous VR experience is very high, but in fact this is a good number taken that the study was conducted in the Netherlands, the fast development of VR technology and its implementation in the daily life. The figures also cohere with previous VR bike experimentation (Bialkova et al., 2018).

Table 4
Model Statistics for Safety (Model 5, encountering the sociodemographics).

AIC = 967.37, BIC = 1461.89, R^2adj = 0.62				
Predictor	$\chi2$	*p*- value	AIC	BIC
Path	18.83	0.004**	974.19	1447.22
Greenness	0.73	0.994	956.10	1429.13
Built up area	8.69	0.192	964.06	1437.08
Car Traffic	26.93	0.0001****	982.30	1455.32
Pedestrian Traffic	2.43	0.876	957.80	1430.82
Intersection	16.56	0.011*	971.93	1444.95
Cleanness	5.98	0.426	961.35	1434.37
VR experience	2.82	0.831	958.19	1431.21
Cycling frequency	2.96	0.814	958.33	1431.35
Gender	4.63	0.592	959.99	1433.02
VR × CyclFreq	8.52	0.203	963.89	1436.91
VR × Gender	6.09	0.412	961.47	1434.49
CyclFreq × Gender	3.97	0.680	959.34	1432.36
Age	13.61	0.034*	968.98	1441.99
Education	11.03	0.087	966.40	1439.42
Household	13.34	0.038*	968.71	1441.73
Kids (number)	15.25	0.018*	970.62	1443.64
Work status	11.22	0.082	966.59	1439.61
Income	16.13	0.013*	971.49	1444.52
Cars (ownership)	11.27	0.081	966.64	1439.66
Bike (ownership)	8.73	0.189	964.10	1437.12
Health status	17.54	0.008*	972.91	1445.93

Note: R^2adj-Nagelkerke. Akaike information criterion (AIC). Bayes information criterion (BIC).
Significance: *p <.05. **p <.01. ***p <.001. ****p <.0001.

Naturalness has not been influenced neither by gender (p >.2), nor by previous VR experience (p >.6). Neither bike ownership (p >.1), nor cycling frequency (p >.2) affected naturalness perception. Concerning presence, neither gender (p >.1), neither previous VR experience (p >.7), nor bike ownership (p >.4) played a role. People who cycled every day evaluated presence to be higher, in comparison to people who cycled at least once per week, as reflected in the marginal effect of cycling frequency (p =.047).

These results suggest that the environment created is reliable, naturally perceived, irrespective of factors gender, previous VR experience, cycling frequency. Therefore, the VR environment could be employed to appropriately address cycling experience as in real bike ride.

4.2. Cycling experience evaluation

To systematically investigate how combinations of the key manipulated factors (Bicycle path, Environmental greenness, Built-up area, Car traffic, Pedestrians/cyclists flow, Intersection, Cleanness) and their interaction influence cycling experience in terms of Safety, Enjoyment, and Attractiveness, logistic regression modeling was performed.

Our model selection procedure considers not only generalisation of cases but also the possibility that different people behave according to different models, or even that the same person experiences cycling specified by different models on different trials. To encompass the possible variations, a step-by-step modelling is run. In particular, the log-likelihood is used, based on summing the probabilities associated with predicted P(Yi) and actual Yi outcomes.

We compare logistic regression models using different subsets of predictors (see Tables 3–8). We estimate the regression weights of each predictor as free parameters; these weights reflect the relative contribution of each predictor in the models. For all models, Akaike Information Criterion (AIC) and Bayes Information Criterion (BIC) are reported, both based on the log-likelihood and in addition penalise for the number of free parameters (for details on the maximum-likelihood-based model selection see Glover & Dixon, 2004).

The basic model was compared with further models, where respectively VR experience, cycling frequency and gender were tested as determining factors. The Model statistics are reported respectively, for Safety (Table 3), Enjoyment (Table 5), and Attractiveness (Table 7). In general, adding VR experience to the base model improved the explanatory power of the model. The model encountering VR experience, cycling frequency and gender had the highest explanatory power.

The final model (model 5) encompassed all factors hypothesised to determine the cycling experience (Bicycle Path, Greenness, Built-up area, Car Traffic, Pedestrian Traffic, Intersection, Cleanness), previous VR experience, cycling frequency, as well as the sociodemographic characteristics (e.g., gender, age, education, incomes etc.). The model statistics are summarised, respectively for Safety (Table 4), Enjoyment (Table 6), Attractiveness (Table 8).

Concerning safety, it was safer to cycle when bicycle path, low traffic volume, and absence of an intersection was experienced (Table 3). Gender effect emerged only on car traffic perception. While female appreciate the low (than high) traffic volume, male seem to be less sensitive to traffic volume (Fig. 3). From the model encompassing the sociodemographics (Table 4), it was confirmed that cycling is perceived to be safer when bicycle path, low traffic volume, and absence of intersection was experienced. People below 20 and those above 60 years old seem to feel less safe on roads. People with kids (6 years old or younger) were more sensitive to safety on

Table 5
Model Statistics for Enjoyment.

Predictor	$\chi 2$	*p*- value	AIC	BIC
Model 1 (Base model: AIC = 219.6, BIC = 391.6, R^2adj = 0.25)				
Path	2.20	0.901	209.76	360.27
Greenness	7.62	0.267	215.19	365.69
Built up area	11.67	0.070	219.24	369.74
Car Traffic	20.58	0.002**	228.14	378.65
Pedestrian Traffic	12.15	0.059	219.72	370.23
Intersection	6.70	0.350	214.26	364.77
Cleanness	2.64	0.853	210.20	360.71
Model 2 (VR experience: AIC = 385.4, BIC = 578.4, R^2adj = 0.27)				
Path	2.28	0.892	375.71	547.72
Greenness	7.64	0.266	381.07	553.08
Built up area	11.68	0.070	385.10	557.11
Car Traffic	20.85	0.002**	394.28	566.29
Pedestrian Traffic	12.14	0.059	385.57	557.58
Intersection	6.64	0.355	380.07	552.08
Cleanness	2.72	0.843	376.15	548.16
VR experience	6.18	0.404	379.61	551.61
Model 3 (VR experience, Cycling frequency: AIC = 478.4, BIC = 693.4, R^2adj = 0.30)				
Path	2.16	0.904	468.60	662.11
Greenness	7.84	0.250	474.28	667.79
Built up area	11.50	0.074	477.94	671.45
Car Traffic	20.55	0.002**	486.98	680.49
Pedestrian Traffic	12.17	0.058	478.61	672.12
Intersection	6.68	0.351	473.12	666.63
Cleanness	2.49	0.869	468.93	662.44
VR experience	6.86	0.334	473.30	666.81
Cycling frequency	10.35	0.111	476.79	670.30
Model 4 (VR experience, Cycling frequency, Gender: AIC = 614.7, BIC = 915.7, R^2adj = 0.39)				
Path	2.57	0.861	605.23	884.74
Greenness	7.91	0.245	610.56	890.08
Built up area	11.94	0.063	614.60	894.11
Car Traffic	20.72	0.002**	623.37	902.89
Pedestrian Traffic	12.79	0.046*	615.45	894.96
Intersection	7.14	0.308	609.80	889.31
Cleanness	2.89	0.823	605.55	885.06
VR experience	3.26	0.776	605.91	885.43
Cycling frequency	14.05	0.029*	616.71	896.22
Gender	6.86	0.334	609.51	889.03
CyclFreq × Gender	7.79	0.254	610.45	889.97
VR × CyclFreq	12.37	0.054	615.03	894.54
VR × Gender	9.34	0.155	611.99	891.51

Note: R^2adj-Nagelkerke, Akaike information criterion (AIC), Bayes information criterion (BIC).
Significance: *p <.05, **p <.01, ***p <.001, ****p <.0001.

roads. People with middle income were least sensitive to safety, while people with high and very low income were more sensitive to safety on roads.

Concerning enjoyment, it was more enjoyable to cycle with low traffic volume (Table 5, Fig. 4). There was a tendency that people enjoyed more the environment with low pedestrians/cyclists flow. Concerning the model encompassing the sociodemographic characteristics (Table 6), it had a better explanatory power, i.e. higher Akaike Information Criterion (AIC) and Bayes Information Criterion (BIC), in comparison to the models reported in Table 5. It was confirmed that low car traffic and low flows of other road participants (pedestrians, cyclists) are crucial for enjoying the cycling. Enjoyment decreased when age, education, and number of kids increased. Actively working people seem to enjoy cycling more than those who are not working (being unemployed, retired, housewife/husband).

Concerning attractiveness, it was more attractive to cycle in green (than no green environment) and within low (than high) traffic volume (Table 7, Fig. 5). Concerning the model encompassing the sociodemographics (Table 8), aging and income influenced the response. For younger people, the environment was more attractive. Environment was least attractive for people above 50 years old. Environment greenness was less attractive for people with low income.

Table 6
Model Statistics for Enjoyment (Model 5, encountering the sociodemographics).

AIC = 971.12, BIC = 1464.64, R^2adj = 0.61				
Predictor	$\chi 2$	*p*- value	AIC	BIC
Path	4.42	0.620	962.54	1435.56
Greenness	9.84	0.131	967.96	1440.98
Built up area	13.88	0.031*	971.99	1445.02
Car Traffic	22.58	0.001**	980.69	1453.72
Pedestrian Traffic	15.20	0.019*	973.32	1446.34
Intersection	7.81	0.252	965.93	1438.95
Cleanness	2.94	0.816	961.06	1434.08
VR experience	3.81	0.702	961.93	1434.95
Cycling frequency	14.39	0.026*	972.51	1445.53
Gender	7.58	0.271	965.69	1438.72
VR × CyclFreq	10.08	0.121	968.19	1441.22
VR × Gender	38.85	0.0001****	996.97	1469.99
CyclFreq × Gender	7.91	0.245	966.03	1439.05
Age	34.69	0.0001****	992.81	1465.84
Education	20.01	0.003**	978.13	1451.15
Household	2.75	0.840	960.87	1433.89
Kids (number)	25.46	0.0001****	983.58	1456.59
Work status	16.67	0.011**	974.79	1447.81
Income	7.58	0.270	965.70	1438.73
Cars (ownership)	10.32	0.112	968.44	1441.46
Bike (ownership)	5.09	0.532	963.21	1436.23
Health status	36.41	0.0001****	994.53	1467.55

Note: R^2adj-Nagelkerke. Akaike information criterion (AIC). Bayes information criterion (BIC).
Significance: *p <.05. **p <.01. ***p <.001. ****p <.0001.

5. Discussion

The present study addressed: How various environmental factors a) traffic volume and pedestrians/cyclists flow, b) infrastructure, c) built-up areas and aesthesis influence both cognitive (i.e. safety perception) and affective (i.e. enjoyment, attractiveness of cycling) responses real time. Immersive VR environments mirroring the streetscape of a real Dutch city were created, and thus providing participants cycling experience as comparable as possible with cycling in real environments. The results are clear in demonstrating that various parameters influence with different magnitude safety, enjoyment and attractiveness of cycling. Factors related to infrastructure (i.e. bicycle path presence and intersection absence) had a positive influence on safety perception. Environmental greenness had a positive impact on attractiveness. Traffic volume had greatest impact on safety perception, but also modulated enjoyment and attractiveness. In the following, we discuss these outcomes in the framework of creating attractive cycling experience that is safe and enjoyable for all.

5.1. *Traffic volume, cyclists and pedestrians*

Traffic volume in terms of cars and other motorised vehicles had a huge impact on safety perception (see Tables 3 & 4). Cycling was considered safer when less cars appeared on the streets. And this effect was strongly pronounced for women (see Fig. 3, middle panel). Note also that traffic volume influenced the enjoyment of cycling (see Tables 5 & 6), as well as its attractiveness (see Tables 7 and 8). Cycling was more enjoyable and more attractive with low traffic volume (see middle panel on Figs. 4 and 5, respectively). Current results confirm H1, for better (safer, enjoyable, attractive) cycling experience with low than high traffic volume.

Furthermore, present outcomes nicely cohere with earlier reports for negative correlation between traffic volume and cycling rates (Foster et al., 2011; Fraser & Lock, 2010). The more intensive the traffic was, the less people were willing to cycle (Pucher et al., 2010). By contrast, people were more motivated to cycle when streets/ routes were away from traffic (Winters et al., 2011). Note, however, that previous studies explored the number of self-reported cycling trips as a measure for cycling, while current study measured real time the bike ride, and thus, zooming-in into the mechanisms underlying the cycling experience itself. Present results demonstrate that traffic volume is a factor that enhances both, the cognitive and affective components of cycling experience.

The impact of other cyclists and pedestrians should also be taken into account, as part of the mobility system. They have been recognised as possible obstacles and causes of accidents (Lawson et al., 2013). Thus, one might expect that increased number of pedestrians/cyclists would impair safety. Opposite to this expectation, pedestrians/cyclists flow did not influence safety perception hereby, i.e. H2 – is not supported. Nevertheless, there was a tendency for more enjoyable cycling when less cyclists and less pedestrians appeared (see Table 5), and particularly in correlation with sociodemographics (see Table 6). This is an interesting outcome worth further exploration, especially in combination of another factors interplay, i.e. infrastructure. It is useful to know whether widening the bicycle path or separating it from the sidewalk would have a positive effect on safety perception, and/or enjoyment of cycling.

Table 7
Model Statistics for Attractiveness.

Predictor	χ2	*p*- value	AIC	BIC
Model 1 (Base model: AIC = 209.8, BIC = 381.8, R^2adj = 0.30)				
Path	11.42	0.076	209.22	359.72
Greenness	33.39	0.0001****	231.18	381.69
Built up area	2.99	0.810	200.78	351.29
Car Traffic	12.77	0.047*	210.56	361.07
Pedestrian Traffic	4.73	0.579	202.52	353.03
Intersection	8.50	0.204	206.29	356.80
Cleanness	12.28	0.056	210.07	360.58
Model 2 (VR experience: AIC = 358.6, BIC = 552.1, R^2adj = 0.33)				
Path	11.50	0.074	358.13	530.14
Greenness	33.57	0.0001****	380.20	552.21
Built up area	2.95	0.815	349.58	521.59
Car Traffic	13.17	0.040*	359.80	531.81
Pedestrian Traffic	4.68	0.585	351.31	523.32
Intersection	8.57	0.199	355.20	527.21
Cleanness	12.01	0.062	358.64	530.65
VR experience	11.82	0.066	358.45	530.46
Model 3 (VR experience, Cycling frequency: AIC = 445.3, BIC = 660.3, R^2adj = 0.34)				
Path	11.69	0.069	445.02	638.53
Greenness	33.28	0.0001****	466.61	660.12
Built up area	2.84	0.829	436.17	629.68
Car Traffic	13.03	0.043*	446.36	639.87
Pedestrian Traffic	4.69	0.585	438.02	631.53
Intersection	8.53	0.202	441.86	635.37
Cleanness	12.05	0.061	445.39	638.89
VR experience	11.35	0.078	444.68	638.19
Cycling frequency	4.24	0.645	437.57	631.08
Model 4 (VR experience, Cycling frequency, Gender: AIC = 578.1, BIC = 879.1, R^2adj = 0.41)				
Path	11.23	0.082	577.30	856.81
Greenness	32.29	0.0001****	598.37	877.88
Built up area	2.89	0.823	568.96	848.47
Car Traffic	13.27	0.039*	579.35	858.86
Pedestrian Traffic	4.39	0.624	570.46	849.97
Intersection	8.82	0.184	574.89	854.40
Cleanness	11.08	0.086	577.15	856.66
VR experience	8.80	0.185	574.87	854.38
Cycling frequency	4.14	0.657	570.21	849.73
Gender	3.65	0.725	569.72	849.23
CyclFreq × Gender	4.92	0.554	570.99	850.50
VR × CyclFreq	10.32	0.112	576.39	855.91
VR × Gender	6.77	0.342	572.84	852.36

Note: R^2adj-Nagelkerke. Akaike information criterion (AIC). Bayes information criterion (BIC).
Significance: *p <.05. **p <.01. ***p <.001. ****p <.0001.

5.2. The infrastructure

The appropriate bicycle infrastructure, i.e. well-designed bicycle path, and intersection absence were crucial for safe cycling, confirming H3 (see Tables 3 & 4). These results cohere with earlier work suggesting that infrastructure (Fishman et al., 2012; Fraser & Lock, 2010), and in particular, bicycle path (Pucher & Buehler, 2008; Verhoeven et al., 2017) is important for cycling. Previous work suggested that providing streets with a bicycle path separated from motorised traffic seems to be the best strategy to increase the street's appeal for adults' bicycle transport (Mertens et al., 2016). Present results clearly demonstrate that infrastructural modifications are crucial in cycling and have greatest impact on safety perception (see Table 9 for a summary).

Intersection absence, as part of infrastructure modification, was another important determinant for safe cycling. Current results oppose previous studies reporting very little influence of intersection on cycling (Lawson et al., 2013; Winters et al., 2011), or no relationship (Fraser & Lock, 2010). A plausible explanation for differences in findings could be the methodology used. Earlier studies used self-reported number of cycling trips (Fraser & Lock, 2010; Winters et al., 2011) or surveys on overall risk perception of a route (Lawson et al., 2013). Hereby, people were cycling real time within VR environments (with and without intersection), and thus having opportunity to experience a bike ride as in real life. In this respect, present study provides a breakthrough methodology in substantiating the effect of infrastructure, real time.

We have to point out here that neither bicycle path presence nor intersection absence modulated the affective response, opposite to H4 assumptions. Current results, however, cohere with previous findings that infrastructural factors might influence the various

Table 8
Model Statistics for Attractiveness (Model 5, encountering the sociodemographics).

AIC = 933.97, BIC = 1428.48, R^2adj = 0.62				
Predictor	$\chi 2$	*p*- value	AIC	BIC
Path	10.69	0.099	939.09	1412.12
Greenness	31.27	0.0001****	959.67	1432.69
Built up area	3.22	0.781	931.62	1404.64
Car Traffic	15.82	0.015*	944.22	1417.25
Pedestrian Traffic	5.55	0.475	933.95	1406.97
Intersection	8.59	0.198	936.99	1410.01
Cleanness	11.21	0.082	939.61	1412.63
VR experience	9.31	0.157	937.71	1410.73
Cycling frequency	7.58	0.270	935.98	1409.00
Gender	7.06	0.316	935.46	1408.48
VR × CyclFreq	9.15	0.166	937.55	1410.57
VR × Gender	4.12	0.662	932.51	1405.53
CyclFreq × Gender	7.53	0.275	935.91	1408.95
Age	16.45	0.012*	944.85	1417.88
Education	4.82	0.568	933.22	1406.24
Household	6.39	0.381	934.79	1407.81
Kids (number)	0.91	0.989	929.31	1402.33
Work status	17.39	0.008**	945.79	1418.81
Income	18.68	0.005**	947.08	1420.09
Cars (ownership)	4.07	0.667	932.47	1405.49
Bike (ownership)	4.32	0.633	932.72	1405.74
Health status	22.45	0.001**	950.85	1423.87

Note: R^2adj-Nagelkerke. Akaike information criterion (AIC). Bayes information criterion (BIC).
Significance: *p <.05. **p <.01. ***p <.001. ****p <.0001.

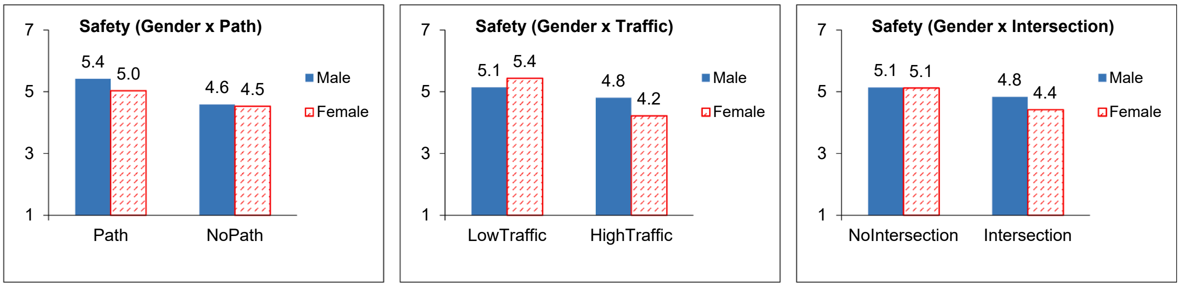

Fig. 3. Safety as a function of Gender (male vs. female), respectively, for factor Path presence (Left panel), car Traffic volume (Middle panel), and Intersection presence (Right panel).

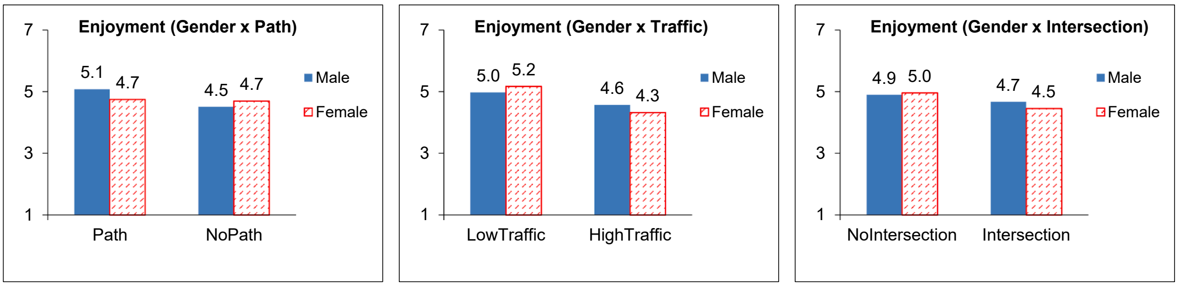

Fig. 4. Enjoyment as a function of Gender (male vs. female), respectively, for factor Path presence (Left panel), car Traffic volume (Middle panel), and Intersection presence (Right panel).

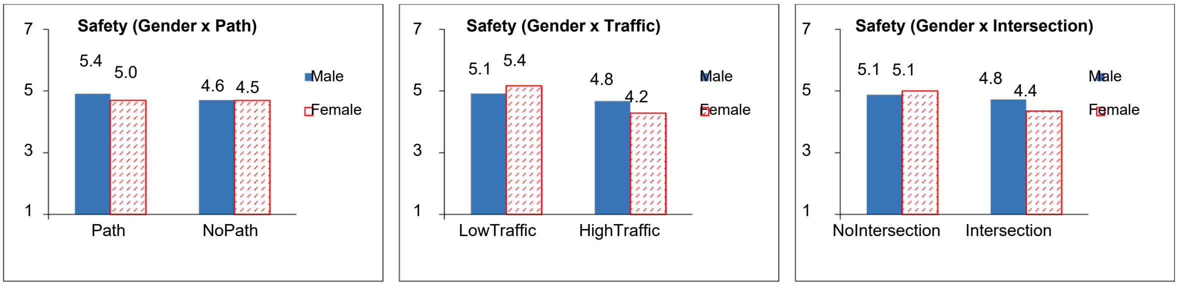

Fig. 5. Attractiveness as a function of Gender (male vs. female), respectively, for factor Path presence (Left panel), car Traffic volume (Middle panel), and Intersection presence (Right panel).

Table 9
Summary of the major effects.

Factor		Safety	Enjoyment	Attractiveness
Infrastructure	Path (present)	✓		
	Intersection (absent)	✓		
Traffic volume	Car traffic (low)	✓	✓	✓
Environment	Greenness			✓

aspects of cycling experience, e.g., safety, enjoyment with different magnitude (Bialkova et al., 2018; Bialkova & Ettema, 2019). Furthermore, hereby the affective component was influenced by other factors related to the environment itself.

5.3. The built-up environment and aesthetics

Environment design, and in particular, built-up typology had an effect on enjoyment of cycling, but did not influence other aspects of cycling experience. We have to mention, however, that this effect was substantiated statistically only in Model 5, encompassing sociodemographics (see Table 6). Mixed built-up area (including shops, restaurants) was enjoyed more, in comparison to residential areas only. Earlier research also noted that a good mixture of built-up area is a prerequisite to increase the number of walking/cycling trips (Saelens et al., 2003; Gao et al., 2018), and in particular in correlation with sociodemographics and travel attitudes (Gao et al., 2019). Increased number of walking/cycling trips with dense built-up areas and high street connectivity was confirmed recently (Verhoeven et al., 2017). Note, however, that increased cycling trips do not necessarily reflect (positive) cycling experience, but rather might be due to the need of doing a trip (Friman et al., 2019; Thorhauge et al., 2020) or the lack of alternative transport (Friman et al., 2017). In the same vein, built-up typology was correlated with other attributes like access, proximity of destination (Friman et al., 2019; van Dyck et al., 2012). Therefore, the impact of built-up typology should be interpreted with caution.

Although a tendency for a more attractive cycling within clean environment, this effect has not been substantiated statistically (all p's > 0.05). Neither safety nor enjoyment perception was cleanness sensitive (all p's > 0.3). Thus, it might be the case that cleanness is not that important for cycling. It might also be the case that cleanses perception depends on some personal factors. Previous study for example reported a difference in cleanness perception between insufficiently and sufficiently physically active people (Lee & Moudon, 2008).

Green environment (i.e. trees, vegetation) was a key determinant increasing the attractiveness of cycling (see Tables 7 and 8), in line with H6. These findings cohere with earlier outcomes for a positive effect of greenness on recreation and cycling (Wendel-Vos et al., 2004; Zlot & Schmid, 2005), i.e. increased self-reported number of cycling trips in green metropolitan areas. Recent work also supported the importance of greenness as appeal for cycling (Mertens et al., 2016). However, the authors noted that the effect of vegetation is pronounced differently depending on whether bicycle path is present or absent. Current study took into account this note and explored the impact of greenness in combination with other factors interplay as appeals for cycling. While greenness influenced how attractive cycling is (H6 - supported), safety seems to do not be affected (H5 - rejected). These results are unambiguous in showing that present work provides methodology to disentangle the cognitive and affective components of cycling experience. Note also, the results showed that enjoyment and attractiveness differ, e.g., Enjoyment has been influenced by Car traffic, but not by Greenness. Attractiveness has been depended on Greenness, but Car traffic had a marginal effect. These outcomes support previous studies that manipulated factors might influence the various aspects of cycling experience with different magnitude (Bialkova et al., 2018, Bialkova & Ettema, 2019). Furthermore, from classical literature in psychology we know that enjoyment reflects core affect (e.g., Russell, 2003; Zevon & Tellegen, 1982), while attractiveness reflects attention and might influence affective component (Scheier & Carver, 1977). In this respect, disentangling various components in cycling experience is a very important contribution of the current work, and provides avenues to further investigate the impact different infrastructure and environment factors might have.

5.4. Sociodemographics

Finally, we have to note hereby that some sociodemographics also enhanced the factors impact. Female (than male) respondents were more sensitive to traffic volume, feeling safer (see Fig. 3, middle panel) and more attracted (see Fig. 5, middle panel) to cycle with less cars on road. Current findings that women put a higher value on safety might explain why less women than men use cycling as a transport mean (Grudgings et al., 2018). Only in countries with bicycle friendly infrastructure the number of actively cycling male and female seems to be pretty equal (Garrard et al., 2008), but then the age determined differences in cycling behaviour (Gao et al., 2017; Gao et al., 2019).

Note that previous studies mainly looked at the number of cycling trips. Hereby we have been able to distinguish how different aspects of cycling are affected, and how these aspects vary for various sociodemographic groups. Concerning safety, age, income, household and number of kids caused some variance (see Table 4) in safety perception. People below 20 and those above 60 years old seem to feel less safe on road. Respondents from households with kids, and with high or very low incomes were more sensitive to safety on road. Concerning enjoyment (see Table 6), there was a strong negative correlation with age, education, and number of kids. Concerning attractiveness (see Table 8), there was a negative correlation with age, and a positive correlation with income. In sum, age seems to be a crucial determinant of cycling. While earlier studies reported that senior citizens cycle more than members of other age groups (Gao et al., 2017), hereby we found a negative correlation between age and cycling experience evaluation. The difference in findings could be due to difference in methodology used. Hereby we evaluated cycling experience real time. The outcomes provide evidences that cycling more often does not necessarily mean it is perceived to be safe and pleasant.

People with kids were also more concerned when it comes to cycling. Incomes seem to be another factor causing variation in cycling experience. Current findings clearly suggest that policy efforts should be directed towards creating safe, enjoyable and attractive cycling environments including the underrepresented age groups (elderly, youngsters, kids), and population with low incomes.

We have to point out here that the present study was conducted in the Netherlands, a country known with a bicycle friendly infrastructure and a relatively high cycling rate (Oakila et al., 2016). Additional research would be good to replicate the study design in a country with not a very well-developed cycling infrastructure and a modest cycling culture. It would be worth looking at how the parameters under investigation (e.g., infrastructure, built-up area, traffic volume and pedestrians/cyclists flow) influence cycling experience evaluation, in a country where a bicycle is not a popular transport mean. Although, in other countries with a less developed cycling infrastructure and culture, similar VR studies needs to be carried out, it seems that attractiveness, safety and enjoyability are important ingredients for cycling policies.

6. Conclusions

Current study addressed the need to underpin subjective evaluations of objective design elements of cycling environments. We offer a more holistic and systematic framework encompassing various cognitive (e.g., safety) and affective (e.g., enjoyment and attractiveness) components of cycling experiences. The suggested immersive VR methodology was able to disentangle various parameters in cycling experience, and thus, to provide in-depth understanding of their underlying mechanisms. Results are very powerful in showing that: 1) Factors influencing safety perception do not necessarily influence in the same way the enjoyment and attractiveness of cycling. 2) Infrastructure parameters, i.e. bicycle path separate from other traffic improved safety perception. 3) Cycling was perceived as safer when intersection was absent. 4) Environmental greenness made cycling more attractive. 5) Low car traffic volume increased safety perception, but also lifted the affective components, i.e. enjoyment and attractiveness of cycling. 6) Women were more sensitive to traffic volume and safety perception, in comparison to men. 7) There was a tendency for more enjoyable cycling with less pedestrians and less cyclists on road. 8) Specific age groups (i.e. elderly, youngsters), and population with low incomes seem to be more sensitive to the influence of the manipulated parameters on safety, enjoyment and attractiveness of cycling.

In sum, Virtual reality is a good methodology to manipulate environmental attributes and to assess in realistic immersive environments various cognitive and affective components of cycling experiences. Present outcomes should be taken into account by urban planners and policy makers in creating infrastructure to appropriately meet the demand for attractive cycling experience that is safe and enjoyable for all.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Tables A1 and A2.

Table A1
Experimental conditions.

Cond	Path	Green	Land Use	Car Traffic	Pedestrian Traffic	Intersection	Clean	Screenshot
1	0	1	0	1	0	1	1	
2	0	1	1	0	0	0	0	
3	0	0	1	1	1	1	0	
4	1	0	1	1	0	0	1	
5	1	1	1	0	1	1	1	
6	1	1	0	1	1	0	0	
7	1	0	0	0	0	1	0	
8	0	0	0	0	1	0	1	

Legend: Path (1 = yes), Green (1 = yes), Land use (1 = residential), Car traffic (1 = yes), Pedestrians/cyclists traffic (1 = yes), Intersection (1 = yes), Clean (1 = yes).

Table A2
Key constructs and measuring scales used in the study.

Construct	Measuring scale	Source
Enjoyment	single item in VR, "I enjoyed cycling in this environment" (1 = "strongly disagree", 7 = "strongly agree")	Self-developed
Safety	single item in VR, "I felt safe cycling in this environment" (1 = "strongly disagree", 7 = "strongly agree")	Self-developed
Attractiveness	single item in VR, "I find this environment attractive" (1 = "strongly disagree", 7 = "strongly agree")	Self-developed
Liking	single item in survey, "I would have liked the experience to continue" (1 = "strongly disagree", 5 = "strongly agree")	Bialkova & van Gisbergen (2017)
Naturalness	4 items in survey "The content seemed believable to me I felt that the displayed environment was part of the real world The scenes depicted could really occur in the real world The displayed environment seemed natural" (1 = "strongly disagree", 5 = "strongly agree")	Lessiter et al. (2001)
Presence	4 items in survey "I felt I was visiting the places in the displayed environment I felt surrounded by the displayed environment I felt I was in the same space as the characters and/or objects shown I felt I could interact with the displayed environment" (1 = "strongly disagree", 5 = "strongly agree")	Lessiter et al. (2001)
Engagement	single item in survey, "I felt involved in the displayed environment" (1 = "strongly disagree", 5 = "strongly agree")	Lessiter et al. (2001)

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