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Compensatory behaviour of visually impaired cyclists in everyday settings

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ABSTRACT

This study investigated whether visually impaired cyclists, compared to cyclists without visual limitations, take other, potentially safer routes to destinations in their own living environment and whether they ride at a lower speed. In total, 19 matched pairs of a visually impaired cyclist and a normally sighted peer from the same neighbourhood recorded their everyday bicycle rides, using GPS action cameras. In addition, they completed an 'assigned ride', a ride for which only a starting and an ending point were provided by the researcher. A risk-assessment procedure showed that the route taken by visually impaired cyclists during this assigned ride was not less risky than the route taken by the normally sighted cyclists. Analysis of the everyday rides showed that, on average, cyclists with a visual impairment more frequently (i.e. for longer periods) cycled at a speed below 10 km/h compared to cyclists without visual impairment. Also, the visually impaired participants' cruising speed was 1.4 km/h lower than that of their normally sighted counterparts. In conclusion, no evidence was found that visually impaired cyclists compensate strategically by taking different, potentially safer routes than normally sighted cyclists when riding in their own environment. They may (unconsciously) compensate tactically for their visual function limitations by riding at a lower speed when necessary. Mobility trainers in vision rehabilitation as well as road designers could apply these findings to optimise the cycling mobility of visually impaired people.

1. Introduction

Cycling as a means of transport is becoming increasingly important and is promoted around the world for a number of reasons, including health, sustainability, and quality of life benefits (e.g. Bonham & Johnson, 2015; Cycling and Walking Australia and New Zealand, 2019; European Cyclists' Federation, 2017; UK Department for Transport, 2020; US Department of Transportation, 2019). In the Netherlands, approximately 25% of all trips are completed by bicycle (Centraal Bureau voor de Statistiek, 2019; Harms & Kansen, 2018). Most Dutch learn to cycle at primary school age (Dessing, De Vries, Graham, & Pierik, 2014; Van Goeverden & De Boer, 2013) and own at least one bicycle (Bovag-Rai Mobiliteit, 2019; Centraal Bureau voor de Statistiek, 2020). The Dutch temperate climate, flat landscape, and high-quality cycling infrastructure likely play an important role for this strong cycling culture.

Cycling could particularly contribute to the independent mobility of visually impaired people. In the Netherlands, contrary to

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driving, there are no legal minimal vision standards that prohibit visually impaired people from cycling. Visually impaired cyclists themselves are responsible for determining whether they can participate in traffic safely without endangering themselves or others. Having this responsibility may be difficult because, in addition to visual functioning, many more determinants are related to safe traffic participation, such as environmental factors (e.g. traffic complexity and infrastructural characteristics), personal factors (e.g. self-confidence and cycling skills), and applying compensation strategies (Cordes et al., 2017; Jelijs, Heutink, De Waard, Brookhuis, & Melis-Dankers, 2018). Dutch rehabilitation centres for people with visual impairments provide advice to optimise the independent mobility of visually impaired people. Occupational therapists of these centres base their cycling advice on practical observations of the client's cycling skills and their looking behaviour in regular traffic.

1.1. Cycling behaviour levels and corresponding risk aspects

Based on Michon's (1971; 1979; 1985) hierarchical structure of road user tasks, cycling behaviour may be divided into three levels as well: the strategic, tactical, and operational level. At the strategic level cyclists make general plans about the trip, for example regarding the trip goals and the route. Typically, there is no time-pressure when making strategic decisions. The tactical level defines behaviour and decisions related to manoeuvring in the prevailing traffic situation, such as overtaking or negotiating crossroads. Cyclists are under moderate time-pressure (seconds) when making tactical decisions. Decisions at the operational level are related to basic skills of vehicle control, such as steering and braking. These decisions are typically automated and subject to high time-pressure (milliseconds).

Michon (1979) relates the strategic, tactical, and operational levels of road user tasks to particular aspects of traffic risk. Cyclists may generate 'risk acceptance', or avoidance, when making strategic decisions. For example, by considering the potential dangers associated with the route and departure time. Typically, 'risk-taking' takes place in parallel with tactical decision-making, as carrying out demanding cycling manoeuvres may increase danger. In case cycling actually becomes risky, it may be necessary for cyclists to 'cope with the threat' by responding quickly to avoid collisions with the object(s) involved. Considering the high time-pressure, this risk aspect typically appeals for automatic decision-making at the operational level of cycling behaviour.

1.2. Cycling with low vision

Visually impaired cyclists may particularly have difficulties at the tactical and operational levels of cycling behaviour as these are subject to time-pressure and based mainly on visual input. For example, a questionnaire study (Jelijs, Heutink, De Waard, Brookhuis, & Melis-Dankers, 2019) showed that crossing intersections without traffic lights and overviewing the situation are among the general difficulties faced by visually impaired cyclists. Other difficulties visually impaired cyclists encounter may be more specific to the nature of the vision impairment. Personal experiences of Connor (1992) suggest that, compared to cyclists with low visual acuity, cyclists with peripheral field loss may swerve more. Cyclists with low visual acuity, on the other hand, may have more wayfinding difficulties (Jelijs et al., 2019).

Despite the fact that safe traffic participation is highly dependent on visual information processing, there is no one-to-one relationship with the nature and severity of visual impairment. An on-road study (Jelijs, Heutink, De Waard, Brookhuis, & Melis-Dankers, 2020) showed that individuals with a very low binocular visual acuity (e.g. BVA = 0.03, Snellen notation: 6/200 or 20/660) or severe peripheral field loss were able to ride an unfamiliar, varying route during daytime independently and safely. As suggested by Connor (1992), visually impaired cyclists may compensate at the strategic level by taking a detour, for example to avoid operational difficulties of overviewing traffic in visually demanding situations. This is in line with the results of a large-scale survey (Jelijs et al., 2019) in which most visually impaired cyclists reported avoiding potentially dangerous situations or manoeuvres by choosing alternative routes or by dismounting their bicycle.

At the tactical level, compensation by cycling at lower speed may result in more time to overview and anticipate traffic. In an experiment where speed was measured at straight continuous road segments in an unfamiliar environment, visually impaired cyclists and normally sighted people cycled at a similar speed (Jelijs et al., 2020). However, daily cycling trips often take place in a familiar environment and include complex situations, such as intersections and turns. Studying the behaviour of visually impaired cyclists in everyday home-town situations may provide further insight into their compensatory decision-making. The geographical restrictions typical for experiments could be overcome by applying the 'naturalistic cycling methodology', which typically involves video recordings and GPS of everyday cycling (Dozza & Werneke, 2014; Gustafsson & Archer, 2013; Johnson, Charlton, Oxley, & Newstead, 2010; Westerhuis & De Waard, 2016). Better knowledge about strategic and tactical compensation in naturalistic settings may contribute to the independent mobility of people with visual function impairments. For example, the results could be used by mobility trainers to further optimise vision rehabilitation as well as by road-designers to improve the accessibility for visually impaired people.

1.3. Aim of the study

The present study aims to provide better insight into the (automated) compensatory behaviour that visually impaired cyclists apply in their own, familiar environment. At the strategic level, we investigate whether visually impaired cyclists take a less risky route than a normally sighted peer when they ride independently to an instructed destination from the same starting point in a familiar environment. Further insight is provided at the tactical level by testing whether visually impaired cyclists ride more frequently at a lower speed compared to normally sighted peers. In addition, at the operational level, the cycling skills of normally sighted and visually impaired cyclists are evaluated based on the videos to provide primary insight in their potential to cope with safety threats.

2. Method

2.1. Participants

Participants were recruited via newsletters and social media of vision rehabilitation centres and patient organisations. They had to ride a single-seat, non-electric bicycle independently (i.e. on their own) and regularly. Participants had to be 50 years or older. Typically, from this age, visually impaired people seek advice because of mobility limitations, for example due to age-related visual impairments (National Health Service, 2021; Popescu et al., 2011). Exclusion criteria were experiencing diplopia, balancing problems, or impaired hearing during cycling. The researchers checked if the participants met the criteria by asking them a number of questions during the sign-up process. Participants signed up in pairs of a visually impaired person and a normally sighted peer from the same neighbourhood. In this way, an effort was made to control for external circumstances and individual differences, for example, the weather, traffic complexity, and age. In all cases the visually impaired person signed up and they nominated the normally sighted peer. The visually impaired persons experienced non-correctable visual function impairment during cycling due to low visual acuity, severe peripheral visual field loss, or a combination of both. The visually impaired participants' visual functions were assessed according to a standardised protocol by low vision specialists at a regional rehabilitation centre of Royal Dutch Visio. Participants wore their own prescription glasses or lenses during the assessment. Binocular visual acuity was measured with the Early Treatment of Diabetic Retinopathy Study test (Ferris, Kassoff, Bresnick, & Bailey, 1982) at 500 lx, visual field with a Humphrey 30–2 threshold test and an Esterman visual field test, and contrast sensitivity with the Vistech Sine Wave Contrast test (Ginsburg, 1984). Using an overlay grid, a visual field score was calculated from the visual field plots' 20–60° (see Colenbrander et al., 1999; Colenbrander, 2001; Cordes et al., 2017). All participants received a financial compensation of €30. The study was approved by the Ethical Committee of the Department of Psychology of the University of Groningen and all participants gave written informed consent.

In total, 21 pairs participated. Two pairs were excluded from further analyses. One participant had not cycled independently during the assessment period and another participant with vision impairment had a binocular visual acuity (BVA) above the criterion of 0.25 (decimals, Snellen notation: 6/24 or 20/80) and no peripheral field impairment. To allow exploration of a potential relationship between cycling behaviour and type of visual impairment, two subgroups were composed. The 'Acuity' subgroup ($n = 10$) consisted of participants with low visual acuity (BVA ≤ 0.25), varying between 0.08 (6/75 or 20/250) and 0.25, without severe peripheral field loss. The 'Field' subgroup ($n = 9$) was, considering the European Union vision standards for driving passenger cars (European Parliament and the Council of the European Union, 2006), composed of the participants seeing <80% of the 50 possible points in 20–60 degrees of the visual field. Two participants in the 'Field' subgroup also had a low visual acuity (0.16 and 0.2). The underlying eye diseases most frequently reported by the visually impaired participants were: macular degeneration ($n = 4$), retinitis pigmentosa ($n = 4$), blindness in one eye ($n = 3$), cataract ($n = 3$), glaucoma ($n = 3$), and nystagmus ($n = 3$). The participants completed a questionnaire providing information about demographics, mental and physical limitations, and cycling frequency (Table 1). None of the participants reported experiencing hearing loss.

2.2. Materials

A Contour GPS + 2 action camera (sample frequency 1 Hz), which features a 170° wide-angle lens, was fitted on the handlebar stem

Table 1
Age, gender, living environment, reported weekly cycling distance, cycling frequency, and vision impairment onset of the normally sighted control participants (C) and the visually impaired participants (VI).

	C ($n = 19$)	VI ($n = 19$)			Total ($N = 38$)
		Overall	Field ($n = 9$)	Acuity ($n = 10$)	
Median age [Q1-Q3]	60 [54–64]	61[52–67]	61 [52–67]	59 [54–69]	61 [54–64]
Gender, male/female (%)	47/53	42/58	33/67	50/50	45/55
Living environment (%)					
Busy urban	11	16	11	20	13
Quiet urban	53	47	56	40	50
Village	21	26	22	30	24
Rural	16	11	11	10	13
Median reported weekly cycling distance, km [Q1-Q3]	25 [20–50][a]	15 [10–50]	15 [11–73]	15 [10–39]	25 [13–50]
Cycling frequency, summer/winter[b] (%)					
Daily	74/74	79/74	78/67	80/80	76/74
Weekly	21/21	16/21	11/22	20/20	18/21
Monthly	5/5	5/5	11/11	-/-	5/5
Onset visual function impairment (%)					
Congenital	–	58	44	70	–
> 10 years ago	–	42	56	30	–

[a] Two participants in this group did not answer the corresponding question.
[b] Participants reported cycling frequency in the summer (May-October) and winter (November-April).

of the participants' own bicycle (see Fig. 1). Participants received an extra battery, a camera manual, and two booklets. The first booklet contained information about the study and the questionnaire (Table 1). The other contained empty 'ride diary' forms, which participants completed after each trip. These forms enabled the researchers to match the videos with basic trip information, such as the date and time, whether the participant cycled on their own, and whether there had been incidents or other noteworthy traffic-related situations.

2.3. Procedure

Data collection took place from April-October 2016 and 2017. After a pair of participants had signed up, the researcher contacted them by phone to check the participation criteria and to agree upon the data collection period, which generally took seven days. If necessary, this period was extended with a maximum of five days, for example if weather conditions prevented participants from using their bicycles in that period.

At day 1 participants were instructed about the study details and the camera usage. In most cases, this occurred during an appointment at a participant's house, where they were also instructed to (1) complete the questionnaire before the next appointment, (2) make video recordings of all of their bicycle rides in the coming week, (3) complete a 'ride diary form' after each trip, and (4) complete an 'assigned ride'. In this 'assigned ride' participants were instructed to cycle on their own from a selected starting point in their neighbourhood to a selected destination point. Starting and destination points were selected in such a way that a comparison between the visually impaired and the normally sighted cyclist would be possible. The distance between starting and ending point was approximately three kilometres. Participants chose the route according to their own personal preference. At the end of the appointment the researcher mounted a camera holder on the participants' bicycle after which the participants practiced attaching and using the camera in compliance with the instructions. At the end of the data collection period the researcher interviewed the participants to collect information about the participants' experiences, including their self-estimated percentage of route-familiarity of the 'assigned ride'.

2.4. Analysis

Rides where participants cycled together with a companion were excluded from further analyses as the focus was on independent cycling. The GPS data included location, speed, local time, and video time. Per ride, each speed sample (1 Hz) was assigned to one of five speed intervals. The lowest cut-off value used for these intervals was set at 5 km/h, being the maximum comfortable walking speed (Bohannon, 1997). Based on Moore, Kooijman, Schwab, and Hubbard (2011) the subsequent cut-off values were increments of 5 km/h, resulting in five speed categories: Very low speed ($\leq$5 km/h), Low speed (5 $<$ km/h $\leq$ 10), Fair speed (10 $<$ km/h $\leq$ 15), High speed (15 $<$ km/h $\leq$ 20), and Full speed ($>$20 km/h).

Each ride's first and last consecutive very low speed samples were excluded from further analyses because participants were on foot when preparing or finishing the ride. Footage in which only very low speed samples were registered for longer than 120 s, the recommended maximum cycle length of traffic control systems ('t Hoen, Vanhuysse, Biekram, & Los, 2014), were inspected and excluded if they were not part of the journey. For example, when the participant forgot to switch off the camera after reaching a destination or took the camera into a supermarket while still recording.

2.4.1. Strategic level: Route choice

The video and GPS data of the assigned ride were cleaned up by determining when the participant crossed a visible landmark (e.g. road edge or manhole cover) at the starting and ending point. Thereafter, the GPS data were cropped and visualised to check whether the starting and ending point corresponded (see Fig. 2). The risk analysis of the route taken during the assigned ride was based on (1) the number of registered bicycle accidents that had occurred at each intersection on the route and (2) a conflict risk rating of these intersections. Intersections were included if the participant crossed the path of potential other vehicles, for example when cycling

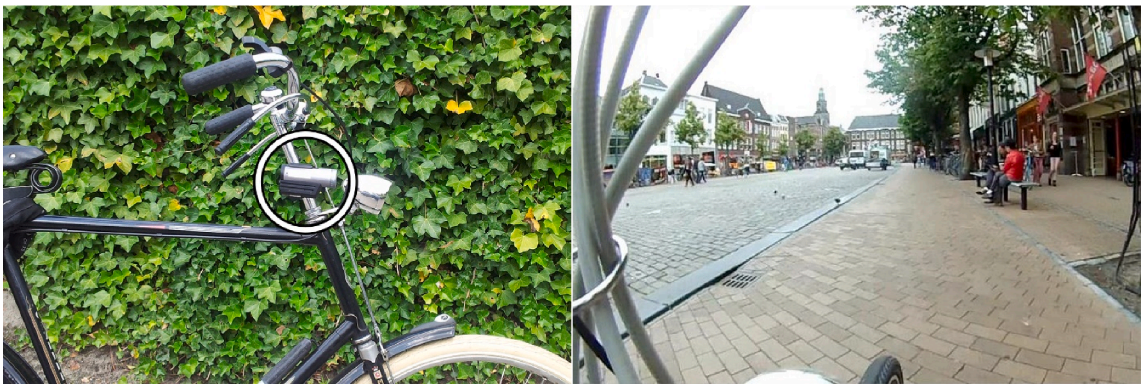

Fig. 1. Camera positioning on the handlebar stem (left) and a view from the camera (right).

straight ahead while passing a side road at the right-hand side. Intersections where participants turned right were included only if the participant had no priority over other traffic.

The number of cycling accidents that occurred at each of the intersections was extracted from an online bicycle accident map (Hastig, 2020). This map is based on the Dutch national road crash registration, which includes bicycle accidents registered by the police between 2014 and 2018. The map provided combined data of fatal accidents and accidents that included physical injury or material damage (see Fig. 2).

The conflict risk rating of the intersections was based on the number of traffic flows the participant had to check and the prevailing traffic intensity during the crossing manoeuvre. The rating varied from 0 to 3, representing respectively 'no or negligible risk' and 'high risk' (see Table 2). The conflict risk rating analysis included the total number of intersections and the total conflict risk score. Because the total risk score represented the sum of the ratings, it did not include intersections that were given a zero score.

2.4.2. *Tactical level: Distance and speed*

Based on all naturalistic rides, each participant's overall cycling distance, proportion of time travelled at a very low or low cycling speed, and cruising speed were calculated. The total proportion of time ridden at a very low or low speed (i.e. $\leq$ 10 km/h) was calculated to determine whether the visually impaired person cycled slower more frequently than their normally sighted peer. The 'cruising speed' was calculated by averaging the speed samples exceeding 10 km/h only. At and above this speed, bicycles are stable practically only by pedalling (Moore et al., 2011) and participants were presumably not being slowed by the prevailing circumstances, such as traffic lights or other road users.

2.4.3. *Operational level: Cycling skills*

Two independent occupational therapists, specialised in cycling instruction and orientation and mobility in visual rehabilitation, evaluated independently and in randomised order the cycling skills of each participant by watching a five-minute video excerpt and completing a digital questionnaire. The video excerpt was selected randomly by a colleague who did not know the participants and their visual condition. The selection only included rides in which the participant cycled without a companion and, if possible, within the built-up area of a city or town. The two evaluators received general information about the study setup, but they were blind to which group the participant belonged. They were instructed (1) to base their answers on the entire video, (2) to rewind only if there was an incident, (3) to spend no more than 15 min on watching one video, and (4) to complete an accompanying questionnaire. The questionnaire consisted of twelve 5-point Likert-type questions about the participant's cycling skills (e.g. speed, lane position, compliance of traffic rules), general safety, and the subsequent cycling advice. The evaluators described using four open-ended questions possible unsafe situations and their (fictional) advice for the participant to follow mobility training. Furthermore, they indicated whether additional information about the visual functioning of the participant would be essential to give a tailored advice. This provided insight into the evaluators' ability to distinguish the visually impaired participants from the normally sighted controls only by watching the video excerpt. For each participant, we calculated the mean of both evaluators' rating per cycling safety aspect. Over these individual scores the median score per group was calculated to provide primary insight into their cycling safety and skills.

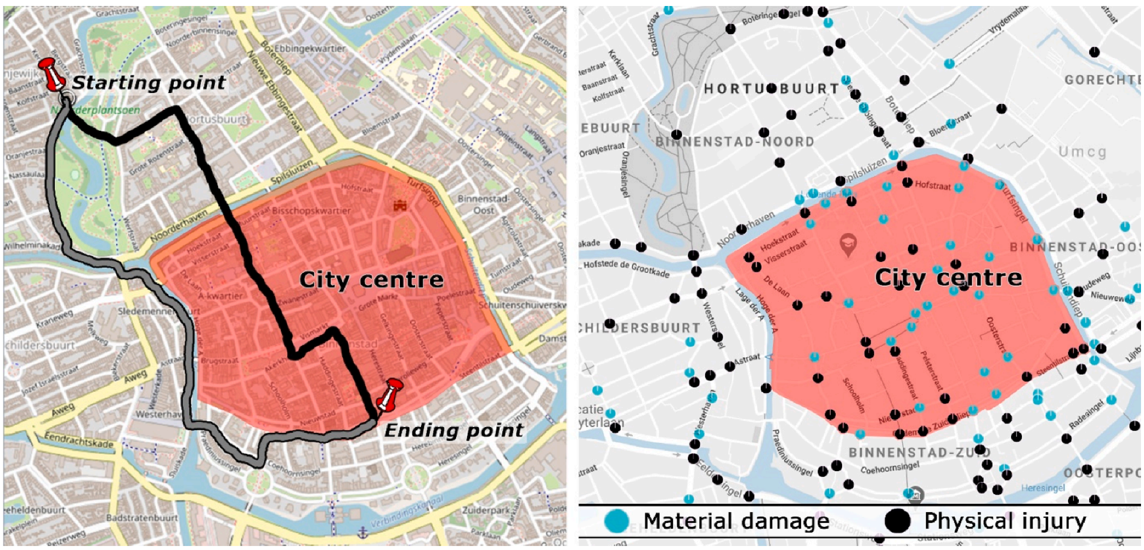

Fig. 2. Illustration of a fictitious pair of participants' assigned ride starting point, ending point, and GPS track results in GPS Track Editor (© OpenStreetMap authors; left) and the corresponding online bicycle accident map (Hastig, 2020; right). The dots on the bicycle accident map represent intersections where at least one registered accident had occurred between 2014 and 2018.

Table 2
Overview of the conflict risk rating definitions used for the risk analysis.

Conflict risk rating	Definition based on traffic intensity and priority	Example
0 - None/ Negligible	Participant has priority over intersecting traffic.	Participants goes straight ahead while riding on a priority road.
1 - Low	Intersection with little traffic (e.g. residential area) and/or a clear overview. Participant has to check one direction for possible oncoming traffic with priority.	Participant goes straight ahead on an intersection in a residential area and has to give priority to the right only.
2 - Medium	Intersection with little traffic (e.g. residential area) and/or a clear overview. Participant has to check two or more directions for possible oncoming traffic with priority. or Intersection with much traffic (e.g. city centre) and/or without a clear overview. Participant has to check one direction for possible oncoming traffic with priority.	Participant turns left on a T-junction in a residential area. or Participant goes straight ahead on intersection in the city centre and has to give priority to the right only.
3 - High	Intersection with much traffic (e.g. city centre) and/or without a clear overview. Participant has to check two or more directions for possible oncoming traffic with priority.	Participant crosses a busy priority road in a city centre.

2.4.4. Statistical analyses

Kolmogorov-Smirnov tests and visual inspection of Q-Q plots pointed out that difference scores were not distributed normally. Therefore, Wilcoxon signed-rank tests were performed, which are denoted by test statistic T (Field, 2009). The significance level was set to $\alpha = 0.05$ for each independent comparison. In order not to increase risk of type II error, significance levels were not adjusted downwards and effect sizes were reported for statistically significant and nonsignificant results. Effect sizes were calculated using Pearson's r (Field, 2009) and were interpreted as large ($r = 0.5$), medium ($r = 0.3$), or small ($r = 0.1$; Fritz, Morris, & Richler, 2012). Inter-rater reliability of the occupational therapists was assessed using two-way mixed, consistency intra-class correlation (ICC; Hallgren, 2012). Based on Koo and Li (2016), the inter-rater reliability was interpreted as poor (ICC < 0.5), moderate ($0.5 \leq$ ICC < 0.75), good ($0.75 \leq$ ICC < 0.90), or excellent (ICC > 0.9).

3. Results

3.1. Strategic level: Route choice

Two pairs, both from the 'Acuity' subgroup, were excluded from the analyses of the assigned ride. The first pair was excluded because insufficient video and GPS data were registered during the assigned ride. The other pair was excluded because one of the participants did not complete this ride on their own. The remaining participants ($n = 34$, 17 pairs) took a route between the starting and ending point that was, on average, 2.6 km long ($SD = 0.7$), which they completed in an average time of 10 min and 20 s ($SD = 142$ sec). Visual inspection of each pair's combined GPS tracks pointed out that five pairs (29%) took exactly the same route. On average, the participants were familiar with the route they had taken ($M = 94.3\%$ familiar, $SD = 11.6$). In total, the conflict risk analysis was based on 595 intersections. Across all participants, the number of intersections varied from 7 to 31 ($M = 17.5$, $SD = 7.0$).

Table 3 shows that the routes taken by the visually impaired cyclists and the normally sighted participants did not differ significantly regarding the total number of registered bicycle accidents, the number of intersections where at least one bicycle accident was registered, and the conflict risk rating. Although the route length did not differ significantly, the visually impaired participants' travelling time to complete the assigned ride was, on average, 79 s longer than that of the normally sighted participants. This is also reflected by the larger proportion of time at which the visually impaired participants cycled at very low or low speed (i.e. ≤ 10 km/h) during this ride. Moreover, the visually impaired participants' average cruising speed during the assigned ride was 1.14 km/h lower than that of the normally sighted participants.

Table 3
Matched-pairs comparisons results of the routes taken by the normally sighted control participants (C) versus the visually impaired participants (VI) during the 'assigned ride'.

	M (*SD*)		*T* [a]	*z*	*p*	*r*
	C	VI				
Total bicycle accidents [b]	11.2 (15.7)	8.8 (11.6)	16.5	−1.126	0.260	-0.19
Intersections ≥ 1 bicycle accident[a]	4.8 (4.7)	4.2 (4.2)	9	−0.853	0.394	-0.15
Conflict risk rating	19.5 (9.1)	18.5 (7.4)	23.5	−1.225	0.220	-0.21
Route length (km)	2.6 (0.6)	2.7 (0.7)	60.5	−0.758	0.449	-0.13
Travelling time (sec)	581 (121)	660 (153)	27	−2.343	0.019	-0.40
Cycling speed ≤ 10 km/h (%)	10.4 (11.6)	16.1 (11.1)	32	−2.107	0.035	-0.36
Cruising speed (km/h)	16.0 (1.7)	14.8 (2.1)	35	−1.965	0.049	-0.34

[a] T represents the Wilcoxon test statistic (Field, 2009).
[b] Bicycle accidents registered between 2014 and 2018.

3.2. Tactical level: Distance and speed

3.2.1. General

The analysis of the naturalistic rides included 430 videos in which the participants ($n = 38$, 19 pairs) completed a total of 1,104 km of solo cycling. This footage included 27 videos (6.3%) of 10 participants (4 normally sighted versus 6 visually impaired) in which they cycled alone in the dark or dusk. None of the participants were involved in serious accidents during the rides that were analysed. Based on the ride diary forms and video inspection a number of minor incidents were observed. For example, there was one minor collision between a visually impaired participant and a child on a bicycle who suddenly came around the corner and one instance where a visually impaired participant just missed a crossing pedestrian. There were seven occasions where participants (six normally sighted and one visually impaired) violated a traffic rule, including running a red traffic light and riding in the wrong direction or on the pavement. Furthermore, there were five occasions where other road users did not give priority to a participant.

3.2.2. Distance

The overall distance of all naturalistic rides varied from 2.6 km to 112.4 km ($Mdn = 22.1$ km, $IQR = 25.8$) for the visually impaired participants and 1.0 km to 59.7 km ($Mdn = 24.4$ km, $IQR = 18.2$) for the normally sighted participants. Two visually impaired participants, both with peripheral visual field limitations, cycled >100 km (see Fig. 3). There was no significant difference of the overall distance cycled by the visually impaired versus the normally sighted participants ($T = 77$, $z = -0.724$, $p = .469$, $r = -0.12$).

3.2.3. Speed

In total, the speed analyses were based on approximately 70 h of video footage that contained valid GPS. The number of seconds registered by the visually impaired participants varied from 685 to 25,781 ($M = 7968.6$, $SD = 7160.2$) versus 205 to 10,919 among the normally sighted participants ($M = 5326.1$, $SD = 3112.8$). Fig. 4 shows that, on average, the visually impaired participants maintained a very low or low speed 18.5% ($SD = 8.9$) of the time versus 11.1% ($SD = 5.5$) among the normally sighted participants. The comparison pointed out that there was a significant difference of the proportion of time travelled at a very low or low speed between the visually impaired and the normally sighted participants ($T = 24$, $z = -2.857$, $p = .004$, $r = -0.46$). Additionally, Fig. 4 shows that for peripheral field loss participants more speed samples above 15 km/h were registered than for participants with low visual acuity.

The cruising speed, which was calculated by averaging the speed samples exceeding 10 km/h, was significantly lower among the visually impaired participants ($T = 44$, $z = -2.052$, $p = .040$, $r = -0.33$). Their cruising speed varied from 11.7 to 18.3 km/h ($M = 14.7$, $SD = 1.8$). On average, this was 1.4 km/h lower than the cruising speed of their normally sighted counterparts, which varied from 12.7 km/h to 21.1 km/h ($M = 16.1$, $SD = 1.9$; Fig. 5). Inspection of the cruising speed by the nature of the visual function impairment suggest a negligible difference between participants with low visual acuity ($M = 14.5$, $SD = 1.9$) versus with peripheral field loss ($M = 14.8$, $SD = 1.8$).

3.3. Operational level: Cycling skills

The group median scores show there were no large differences between the cycling skills and safety of the normally sighted and the visually impaired participants. As presented in Table 4, they received the same median score in seven of twelve cycling aspects, including speed, distance to the kerb, and cautiousness. There were minor differences between the ratings of the other five cycling aspects, for example lane control, obeying the rules, and self-confidence. A moderate inter-rater reliability was found for the overall 'cycling advice' (ICC = 0.62). The inter-rater reliability on the remaining specific subscales ranged from 'poor' (ICC = -0.19) to 'good' (ICC = 0.79).

Based on the entire five-minute video excerpts, both evaluators indicated whether they would overall 'recommend' the participants to cycle independently (see Table 4, cycling advice). Eight normally sighted (42%) versus ten visually impaired participants (53%) were (strongly) recommended to cycle by both evaluators. None of the participants were discouraged by both evaluators, but in two normally sighted (11%) versus three visually impaired (16%) participants one evaluator discouraged cycling. In both cases where normally sighted cyclists were discouraged, the other evaluator indicated being 'not sure'. In all three cases where visually impaired

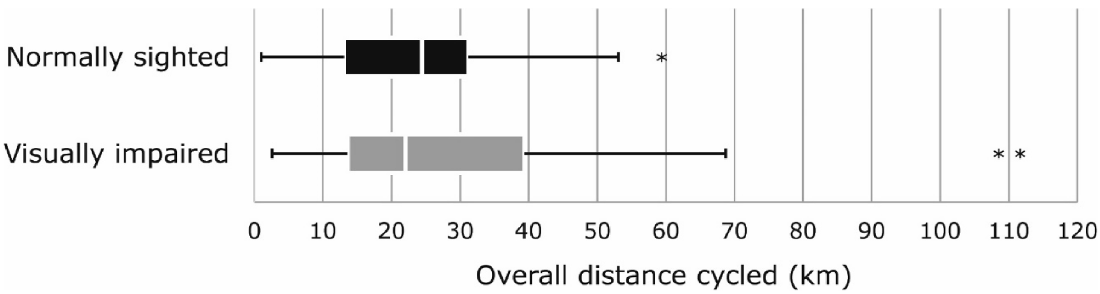

Fig. 3. The distribution of the overall distance of the naturalistic rides of the normally sighted (Mdn = 24.4, IQR = 18.2) versus the visually impaired (Mdn = 22.1, IQR = 25.8) participants. Outliers (*) were values 1.5 times the IQR larger than the third quartile.

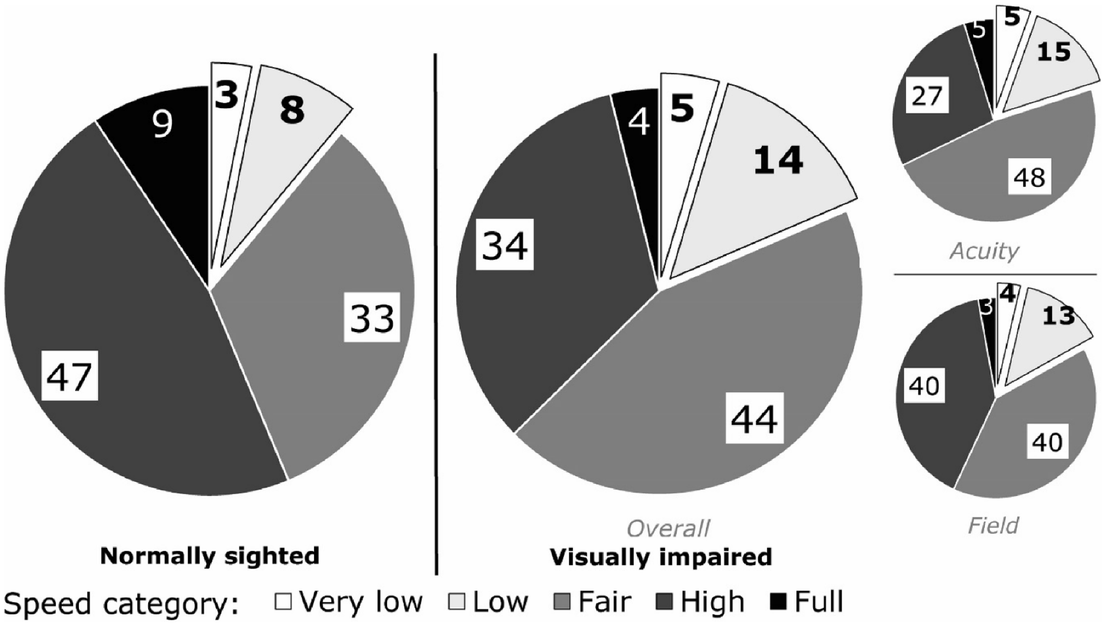

Fig. 4. The naturalistic rides speed category distributions (in percentages) of the normally sighted versus the visually impaired participants. These distributions were established by averaging the individual proportion of speed samples classified as Very low (0 < km/h ≤ 5), Low (5 < km/h ≤ 10), Fair (10 < km/h ≤ 15), High (15 < km/h ≤ 20), and Full (>20 km/h).

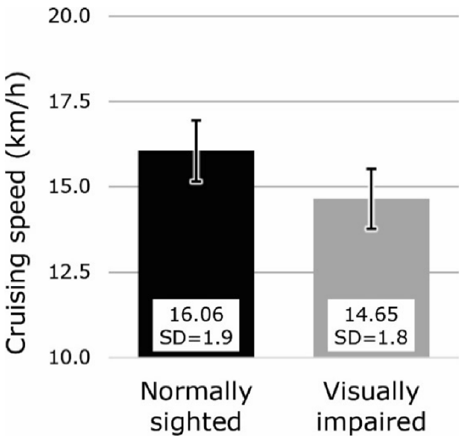

Fig. 5. The overall cruising speed of the normally sighted versus visually impaired participants. These values were established by averaging the participants' individual cruising speed, which included speed samples that exceeded 10 km/h only. The error bars represent the 95% confidence interval.

cyclists were discouraged, the other evaluator recommended cycling.

Six participants, five of which normally sighted (26%) and one visually impaired (5%), were recommended unanimously by both evaluators to follow mobility training. The evaluators indicated that these participants needed traffic rules training or cycling training in higher traffic intensity. In the case of 10 normally sighted (53%) and nine visually impaired (47%) participants at least one evaluator indicated that additional information about the visual functioning would be essential to give a tailored advice. In both groups there were three (16%) cases where the evaluators indicated unanimously that more information about the visual functioning would be essential. All this implies that the evaluators had difficulties to distinguish the visually impaired participants from the normally sighted controls based on the five-minute video excerpt alone.

4. Discussion

The present study aimed to provide insight into the possible compensatory behaviour on the strategic and tactical level (Michon, 1971; 1979; 1985) of visually impaired cyclists during everyday cycling. The present study does not show that visually impaired

Table 4
The group median ratings (dark grey) after averaging both occupational therapists' evaluations of the cycling safety of the normally sighted control participants (C) and the visually impaired participants (VI). There were seven ratings where the overall median covered two values (light grey).

Speed	C	Much too low	Too low	**Normal**	Too high	Much too high
	VI	Much too low	Too low	**Normal**	Too high	Much too high
Lane control	C	Very poor	Insufficient	**Sufficient**	**Good**	Excellent
	VI	Very poor	Insufficient	**Sufficient**	Good	Excellent
Braking smoothness	C	Not fluent	Somewhat fluent	Fairly fluent	**Fluent**	Very fluent
	VI	Not fluent	Somewhat fluent	**Fairly fluent**	**Fluent**	Very fluent
Distance to traffic	C	Very poor	Insufficient	**Sufficient**	**Good**	Excellent
	VI	Very poor	Insufficient	**Sufficient**	**Good**	Excellent
Distance to kerb	C	Much too small	Too small	**Normal**	Too large	Much too large
	VI	Much too small	Too small	**Normal**	Too large	Much too large
Anticipating circumstances	C	Much too early	Too early	**Normal**	Too late	Much too late
	VI	Much too early	Too early	**Normal**	Too late	Much too late
Obeying rules	C	Very poor	Insufficient	**Sufficient**	**Good**	Excellent
	VI	Very poor	Insufficient	Sufficient	**Good**	Excellent
Cautiousness	C	Much too cautious	Too cautious	**Normal**	Too incautious	Much too incautious
	VI	Much too cautious	Too cautious	**Normal**	Too incautious	Much too incautious
Confidence level	C	Not self-confident	Somewhat confident	Fairly self-confident	**Self-confident**	**Very self-confident**
	VI	Not self-confident	Somewhat confident	Fairly self-confident	**Self-confident**	Very self-confident
Judgmental errors	C	Very often	Often	Occasionally	**Rarely**	**Never**
	VI	Very often	Often	Occasionally	Rarely	**Never**
Safety level	C	Very unsafe	Unsafe	Not sure	**Safe**	Very safe
	VI	Very unsafe	Unsafe	Not sure	**Safe**	Very safe
Cycling advice	C	Strongly discourage	Discourage	Not sure	**Recommend**	Strongly recommend
	VI	Strongly discourage	Discourage	Not sure	**Recommend**	Strongly recommend

cyclists take a safer route than their normally sighted peers. Furthermore, there was no difference in length between the routes taken by the visually impaired and those taken by the normally sighted participants. This suggests that, in their own familiar environment, the visually impaired cyclists do not necessarily take a detour or avoid potentially dangerous or visually demanding traffic situations. This finding is in contrast with a larger-scale survey study ($N = 328$) performed in the Netherlands (Jelijs et al., 2019). The large majority (81%) of the visually impaired respondents of the survey, versus 14% of the normally sighted, reported they avoid situations, such as complex traffic situations. Other environmental factors such as traffic density could have played a role, however, the ratio of urban–rural living environment was similar to that of the present study's participants (approximately 60%-40%). Connor (1992) also emphasised, based on his personal experiences, the relevance of route planning and avoiding difficult circumstances for cycling with visual function impairments. The present findings may also indicate that the visually impaired participants were not triggered to take a different route during the assigned ride. Complex or high dense traffic situations within three kilometres of the participants' house(s) were scarce in a number of cases. Especially in rural areas, taking a detour could have been unviable as there was only one sensible route between the allocated starting and ending point.

At the tactical level (Michon, 1985), the visually impaired participants spent significantly more time travelling at a speed below 10 km/h than the normally sighted cyclists. This potentially reflects that these participants were watching out for traffic or approaching intersections (see Connor, 1992). Visually impaired cyclists may need not only more time to cover the same distance as normally sighted cyclists, but also more space as cyclists are balancing their bicycle at a speed below 10 km/h (Moore et al., 2011). Road designers may take this into account, for example by installing 'cycling refuge islands' to give visually impaired cyclists more time to cross a street and check for oncoming traffic or by ensuring they have sufficient space to balance their bicycle at a speed below 10 km/h. The visually impaired cyclists' average cruising speed was 1.4 km/h lower than that of normally sighted cyclists. Mobility trainers in vision rehabilitation may raise awareness about these speed compensation strategies. It is possible that these speed differences are the result of the increase in family-wise error rate across the tests. However, the according effect sizes are substantial and the low power associated with naturalistic research, characterised by external circumstances that are difficult to control, would typically increase the probability of type II error. We encourage replication of this study with more participants, and in other parts of the world. Future research should provide a more detailed insight into the speed decisions of visually impaired cyclists, for example when they approach intersections. This could be operationalised by assigning participants a gap-acceptance task in a controlled setting, for example using a bicycle simulator (Dialynas, Happee, & Schwab, 2019).

The occupational therapists' evaluations suggest that, at group level, the visually impaired cyclists and the normally sighted controls could not be distinguished by their cycling skills or safety. Based on the video excerpts, the visually impaired and normally sighted participants received virtually identical overall ratings of the cycling aspects, representing mainly operational (Michon, 1985) cycling behaviour. This implies that, at group level, the visually impaired cyclists acquired the operational skills to cycle, contributing to their ability to 'cope with safety threats' (Michon, 1979).

4.1. Study strengths and limitations

This study provides an authentic insight into the participants' daily cycling behaviour as they rode their own bicycle in their own environment to reach their everyday destinations. We collected a large amount of data in a wide variety of environments, involving cycling behaviour at each level of Michon's (1971; 1979; 1985) hierarchical structure of road user tasks. Similar to previous research in this field (e.g., Jelijs et al., 2020; Wilhelm & Endres, 2004), the present sample included participants with severe visual function limitations, making the findings potentially applicable to a variety of cases in which a visually impaired person wishes to cycle. It is, however, unclear how well the present findings represent cycling with recently-acquired visual function limitations as the participants' vision limitations arose longer than 10 years before participation. It is also unknown to which extent the present findings are applicable to cyclists younger than 50 years and to other countries. Visually impaired cyclists may benefit from the strong cycling culture and high quality cycling infrastructure that are present in countries such as the Netherlands.

There were limitations related to the study setup. Possibly, there was a difference between the visually impaired participants' and normally sighted participants' motivation to participate to this study. The visually impaired participants were possibly more dependent on cycling, which may also explain their larger variation and the two outliers in the total distance of all naturalistic rides. There were inaccuracies of the speed measurements as the camera could occasionally not register the speed due to GPS disruptions, for example in tunnels or near high buildings. Furthermore, the participants' involvement in unsafe situations is potentially underestimated. The participants would not register unsafe situations which they did not perceive as 'unsafe' and the camera did not provide a full 360° view of the traffic situation. In a number of rides the view was further limited because the camera was positioned incorrectly before the ride. Possibly, compared to the naturalistic rides, the assigned ride represented to a lesser extent the participants' naturalistic behaviour as they might have been aware that this ride would be analysed thoroughly.

The occupational therapists' ratings of the cycling skills and safety should be interpreted with caution. Typically, they do not use video data to assess cycling safety. Instead, for this study they could use only very limited information: compared to regular assessment the video excerpts were short and did not show the participants' head and eye movements and did not always include a variety of traffic situations or densities. The occupational therapists thus did not have a full view of the traffic situation and were probably unfamiliar with most areas in which participants were riding, which possibly made it harder to understand the participants' behaviour. Furthermore, we found a moderate inter-rater reliability for the overall cycling advice. This reflects that there were inconsistencies between the evaluators' overall impression of the cycling skills of the participants. Low variability of answers in a number of the other subscales prevented calculation of meaningful inter-rater reliability estimations (e.g. ICC or weighted kappa; see Hripcsak & Heitjan, 2002; Koo & Li, 2016). In rehabilitation practice, video recordings of everyday cycling may not equate a traditional, real-world cycling safety assessment. Instead, they could serve as a 'screening tool' for occupational therapists, for example to tailor the urgency and contents of cycling training to their clients during or in preparation of mobility training. Because the evaluators perceived relatively much unsafe behaviour, including in the normally sighted cyclists, we recommend taking the limitations of our approach into account before using video excerpts in the present form as a screening tool.

4.2. Conclusion

There are visually impaired persons, even with severe visual function impairment, whose cycling skills and safety may not be distinguished from those of the normally sighted cyclists. The present study shows that visually impaired cyclists do not necessarily compensate at the strategic level by taking safer routes than normally sighted cyclists. There are indications that visually impaired cyclists compensate (automatically) at the tactical level by spending more time travelling below 10 km/h and, when presumably not being slowed down by other traffic, by cruising at lower a speed compared to normally sighted cyclists. Road designers may take into account that visually impaired cyclists ride more frequently at a low speed, which may require both extra time and space. Mobility trainers in vision rehabilitation could use the present insights when giving cycling advice.

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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