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Improving the visibility of bicycle infrastructure

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Abstract: The visual characteristics of road infrastructure play a major role in a substantial number of single-bicycle crashes. The focus of this research was on finding the most common situations that result in a poorly visible bicycle infrastructure, and investigating how to improve these conditions for vulnerable cyclist populations, specifically the visually impaired and the older cyclist. Three studies were performed, a questionnaire study amongst visually impaired cyclists, focus group discussions with older cyclists, and an experiment on a closed track where participants' vision, in particular their contrast sensitivity, was impaired. The results from the questionnaire study and the focus group discussions revealed that bollards, kerbs, and cycle path markings/shoulders are the most critical visual elements in the road infrastructure. In addition, cycling performance and cyclists' feelings of safety worsened in conditions where the visibility of obstacles and the road's course were the poorest. Visibility can be enhanced by placing red-white bollards, painting kerbs white, by enhancing clearness of the road's shoulder, or by applying high contrast road markings on the side of the cycle path/road.

Keywords: visibility; bicycle; single-bicycle crash; cyclist; infrastructure; obstacles; bollards; contrast; ageing.

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1 Introduction

1.1 Single-bicycle crashes

The majority of accidents that involve a cyclist do not involve any other traffic (van Kampen, 2007; Larsson, 2008). In the Netherlands, approximately 46,000 cyclists receive treatment in Emergency Care Departments each year as a result of single-bicycle crashes (LIS, 2007) and 6,000 of these cyclists are hospitalised each year. This is one third of all hospitalisations related to road accidents and this number increased with 50% between 1984 and 2005 (van Kampen, 2007). Single-bicycle crashes also make up a fairly large part of the total number of traffic fatalities. In 2005, for example, the share of single-bicycle fatalities in the Netherlands was 38%. Taken over time, this accounts for the death of approximately 50 individuals per year in single-bicycle crashes (Ormel et al., 2008).

Causes of single-vehicle crashes are diverse (Ormel et al., 2008), some are related to balance problems (skidding due to ice on the roadway, but also loosing balance during mounting and dismounting), some are related to mechanical failure. Distraction [almost 2% mobile phone use and 2% listening to music (Ormel et al., 2008)] and the use of alcohol [5% to 25%, Nyberg et al. (1996)] also play a part in the cause of single-bicycle crashes (Schepers et al., 2009).

About one out of four single-bicycle crashes is a collision with an obstacle on the road or running out of lane (Schepers and Den Brinker, 2011). The visibility of bicycle infrastructure and obstacles were considered to be the main contributing factor (Schepers et al., 2009; Ormel et al., 2008) in a further 25% of single-bicycle crashes. Generally, more accidents occur during the hours of darkness (Reurings, 2010), and it is not surprising that accidents contributed to poor visibility are also more common during these times (Schepers and Den Brinker, 2011). Older cyclists are prominently represented in single-bicycle accidents (Schepers and Den Brinker, 2011; Leden, 2008).

1.2 Visibility of bicycle infrastructure

Knowledge about which aspects in the bicycle infrastructure are particularly poorly visible is limited. From studies on car driving we know that visual information is important and matters. Studies by Wood and Troutbeck (1995) and Wood (2002) have shown how important visual impairment is in driving for older drivers. There are some studies that have shown the importance of visual guidance for driving, mainly with regard to lane control and speed (McKnight et al., 1998; de Waard et al., 2004). Effects of visual road safety engineering treatments were shown by Jamson et al. (2010). With respect to the bicycle infrastructure, Schepers (2008) found that in 19% of single-bicycle crashes, cyclists ended up off the road or cycle path. Since cycle paths often do not have road markings this could suggest that, similar to main roads with motorised traffic, the absence of road markings may contribute to single-bicycle-off-road accidents (Schreuder and Schoon, 1990). In a further 7% of bicycle accidents, a bollard or other stationary obstacle was hit (Nyberg et al., 1996; Schepers, 2008). These obstacles are placed in the bicycle infrastructure deliberately, to prevent access by cars. In a recent study (Schepers, 2008), several single-bicycle crash scenes were inspected. It was found that road edges and obstacles were often poorly visible at crash locations where cyclists rode off the road or collided with bollards or road narrowings. Visually impaired cyclists and older cyclists were more frequently involved in these crash types (Schepers and Den Brinker, 2011).

1.3 Ageing and cycling

In 2009 in the Netherlands, almost 60% of all seriously injured road casualties (Reurings and Bos, 2011) and 25% of all fatalities (Statistics Netherlands, 2010) were cyclists. Cyclists are over represented in accidents when compared with other groups of traffic participants, meaning that improvements in bicycle infrastructure could have a significant road safety impact. In particular, improving the safety of bicycle infrastructure is relevant for older cyclists because of their higher reported accident involvement rate, vulnerability to injury, and the higher subsequent costs of their healthcare (Methorst, 2003). Ormel et al. (2008) showed that the number of single-bicycle crash victims treated at Accident and Emergency Departments and admitted to hospital per kilometre travelled by bicycle is increased amongst the elderly population. A cyclist of 75 years or older runs a 12 times higher risk of dying in a crash than an average cyclist does (Ministry of Infrastructure and Environment, 2008). As with most Western populations, the Dutch population is ageing, and consequently the group of vulnerable road users is growing. In 2020 the Netherlands is expected to have 3.3 million inhabitants aged 65 years and older, which will account for almost 20% of the total population (Ministry of Infrastructure and Environment, 2008).

Despite the relatively large road safety risks, it is essential that older people are able to continue to use their bicycles. Cycling improves their health, their quality of life, and reduces the risk of heart disease. de Hartog et al. (2010) showed that for people who shift from car to bicycle use for short trips, the largest estimated gain in additional years of life was for the elderly. Furthermore, bicycles are an important means of transport for people aged 50 to 75+ in the Netherlands (van Loon and Broer, 2006). Not being able to cycle anymore would mean reduced mobility and a loss of independence and would impact mental well-being (Kaiser, 2009; Mollenkopf et al., 1997). Also for people who do not have a driving licence because their visual acuity has decreased to 30/60, or for people whose spouse who had a driving license has died, cycling can be the only efficient means of independent transport.

1.4 Vision and cycling

With increasing age, visual acuity, visual field size, contrast sensitivity, and glare sensitivity decrease (Boyce, 2009). In particular a decreased detection of motion, glare sensitivity, and contrast sensitivity are important for performance in traffic (Brouwer, 1996). In groups with visual impairments, contrast sensitivity and visual field are correlated with mobility performance (walking), whereas visual acuity is not (Marron and Bailey, 1982; Long et al., 1990). In an experiment involving driving in a car on a closed-road circuit, Wood et al. (1994) found a positive effect of (artificial) visual field restriction on driving performance. Significant correlations between contrast sensitivity and driving performance have also been reported (Coeckelbergh, 2002).

1.5 This research

In total, three studies on the relation between infrastructure and cycling with reduced vision were performed. The aim of the first two studies was to enable a focus on relevant critical situations in the third study. In the first study, a group of visually impaired people were asked to indicate which situations they perceive to be visually problematic while cycling. In the second study, this topic was discussed with a group of older cyclists. In the third study, the visual field and contrast sensitivity of participants was artificially decreased, and participants had to cycle over a track that contained visually problematic situations that were based on the results of studies 1 and 2. Cyclists' behaviour was observed, participants were asked to rate the different conditions on visibility and safety, and cycle speed was measured. Although improved visibility of the road alignment for cars can increase driving speeds (Tenkink, 1988; Steyvers and de Waard, 2000) and accidents (Kallberg, 1993), in the present research increased speeds were only taken as a positive sign, i.e., as a reflection of better visibility.

2 Methods Studies 1 and 2

Study 1 was a questionnaire study. Questions were asked regarding situations with poor visibility, the potential danger these pose to cyclists, and the consequences these situations have for cycling behaviour and crash involvement. The questionnaire was sent to 150 members of the Association for Macular Degeneration. Macular Degeneration is an ocular disease which causes damage to the central part of the eye's retina (the macula). In the Western world, age-related macular degeneration an important cause of visual impairment (Coeckelbergh, 2002), which is why this group was selected for the study.

In Study 2, group discussions were organised for normally sighted people aged 65 years or older. These meetings were held in Amsterdam, the largest city in the Netherlands, where tram tracks can be encountered as a problem for cyclists, and in Groningen, a smaller city surrounded by a rural area. The discussion meetings were structured through use of a PowerPoint presentation containing illustrations of different situations of the bicycle infrastructure. Forty-seven illustrations of situations with bollards, road narrowings, kerbs, and (missing) road markings were shown and after presentation participants responded to what was shown. They were asked whether each situation would pose visual problems for them, and if so, what consequences these situations would have for them as cyclist.

2.1 Results studies 1 and 2

The questionnaire for Study 1 was returned by 68 people (45%), with an average age of 59.4 years (SD 15.3) and a self-reported average visual acuity for both eyes of 0.32 (which equals 0.48 LogMar). Four respondents reported that they had quit using their bicycles partly due to visual problems and almost 60% of the 68 respondents indicated that poorly visible situations affected their cycling behaviour.

The two situations that were most often mentioned by the respondents as being poorly visible involved kerbs and other elevated surfaces (47%), and bollards and access barriers (44%). Road narrowings (21%) and the visibility of the road's course (26%) were also mentioned quite often. Encountering these situations resulted in reporting slower, more careful and restricted cycling behaviour by 25% of the respondents. Feelings of insecurity and anxiety were reported by 18% of participants in reaction to these situations and in a single case even resulted in reports of dismounting from the bicycle and passing the location on foot.

Of all respondents of Study 1, 45% reported to have fallen or to have bumped into an obstacle while cycling, and 76% said that they avoid certain situations because these are poorly visible. Most reported crashes involved hitting kerbs (26%) or bollards (23%), and situations where the shoulder did not have high enough contrast with the road surface (13%). Respondents considered these three situations the most important ones to improve and stated that this could be done by improving the clarity of faded road markings, applying road delineation on the edge of the cycle path or road, the whitening of kerbs at crossings and by painting bollards in distinctive colours. They also indicated that they would cycle more often if these measures were implemented.

In Study 2, a total of 16 people participated in the discussion meetings, eight in Amsterdam and eight in Groningen. When asked which situations they considered to be the least visible in general, they commonly answered 'unexpected situations', such as tunnels with sharp curves, anything with too little contrast compared to its surroundings (e.g., bollards, the road versus the shoulder), and the absence of road markings in the centre of a bicycle path to indicate two way traffic.

Specific examples of situations shown to participants generated strong negative reactions. These situations consisted of bollards, road narrowings, kerbs and different road designs. Bollards and road narrowings can be particularly unexpected aspects of a cycle route. They are often used to but are not of any particular use to cyclists, except that they keep cars off the cycle path. Unsurprisingly if an obstacle is not expected, it is less likely to be noticed (Bakken et al., 2007). Situations with kerbs mostly cause problems in areas with busy traffic. For older cyclists these situations demand more of their restricted capacity and as a result they are more likely not to see kerbs and other elevated surfaces.

According to participants painting bollards in more distinctive colours and making road narrowings, kerbs and the road's course more conspicuous (e.g., by painting these white) would improve the visibility of bicycle infrastructure for the older cyclist. The participants would also like to see as few bollards as possible, and where these cannot be avoided they should have two colours and there should also be a warning using lights, road signs and signals on the road surface.

2.2 Discussion and conclusions Studies 1 and 2

Study 1 and 2 can be criticised because they focus on subjective safety (i.e., personal feelings experienced by cyclists regarding the lack of safety in traffic), which might be only weakly related to objective safety (i.e., the occurrence of single-bicycle crashes). However, the findings of Studies 1 and 2 correspond with results from a recent study on the role of the visual design of the infrastructure in single-bicycle crashes in which it was found that the guidance and conspicuity of obstacles was important (Schepers and Den Brinker, 2011). Furthermore, feeling unsafe in traffic can lead to road users limiting their mobility (SWOV, 2009), which would impact on the Dutch Government aims to increase the level of bicycle use (Ministry of Infrastructure and Environment, 2005).

On the basis of results of both studies it can be concluded that specific situations in the infrastructure are related to cycling problems. In particular kerbs, bollards, the road's course, and situations with low contrast form a problem as they lead to collisions or falls, avoidance behaviour, and feelings of insecurity and anxiety.

3 Study 3

3.1 Method

Study 3 was an outdoor experiment. The results of Studies 1 and 2 delivered the critical situations that would be evaluated in Study 3. These included kerbs, bollards, road narrowing, and a situation where the road's course is unclear. In particular bollards were presented in several 'everyday' versions (referred to as standard), which are familiar to participants (the black and the red-white bollard), and in potentially improved versions, with multiple colours, lights or warning signals on the road surface. A yellow-black diagonal bollard for instance was chosen because it consists of two colours, one dark and one bright to improve contrast both in light and dark conditions. In Study 2, participants stated that yellow was a bright colour well visible to them (unlike red) and the colour black would make bollards better visible in bright sunlight conditions. Kerbs were presented in unmarked and marked versions, including a version that was painted white. Situations with an unclear road course were created by the absence of road markings combined with a shoulder of grass, resulting in little contrast between the road surface and the shoulder (i.e., a small difference in brightness). In order to allow for comparisons there was also a condition with a clearly visible shoulder. Furthermore, to investigate the effects of the road's course, two versions of road markings on the edge of the road were included, one having a high clarity and the other one with faded markings. All conditions are summarised in Table 1 and some examples are shown in Figure 1. All conditions were presented to all participants in 16 trials, balanced in order over participants based on a Williams design (a type of Latin Square). This means all participants cycled the track 16 times. The circuit was a closed outdoor track. Despite negative aspects such as having no control over the weather, ecological validity benefits from such a location. On the track a cycle path was mimicked by a white rope. The rope enabled to make quick changes in the course of the path, between the different conditions. The curvy cycle path was one metre wide on asphalt surface, the total track was 280 metres long. All obstacles were made of light weight material so that colliding with bollards or kerbs would not lead to injury or falls.

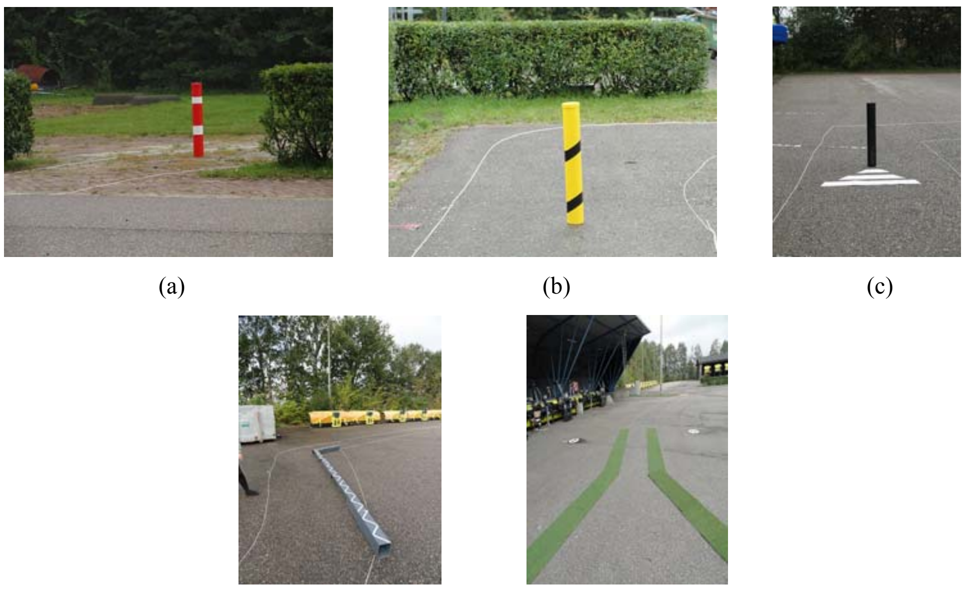
Every participant had to wear adapted safety goggles to reduce their contrast sensitivity and visual field in all conditions. This was achieved by gluing varying layers of plastic to the front of four sets of safety goggles, resulting in different degrees of contrast sensitivity in each set of goggles. Visual acuity was also reduced by the layers of plastic, and the silicon plastic on the side of the goggles acted to reduce visual field. To ensure that each participant's contrast sensitivity was similar they first had to perform a contrast test [the Groningen *edge* contrast *chart* Gecko (Kooijman et al., 1997, see also van Gaalen, 2009)]. Participants first had to wear the goggles that reduced their contrast sensitivity the most and then had to attempt to identify as many items on the Gecko chart as possible, starting with the easiest item. Subsequently, they had to repeat the test with the other glasses until the eight-item could be identified. The goggles they were wearing when this item could just be identified were the goggles they had to wear during the experiment.

Table 1 The 16 conditions all participants completed in Study 3

Bollards	*Kerbs*	*Shoulder*	*Road markings*
Black (standard)	Grey (unmarked)	Grass	High contrast
Black flashing light*	White	White pavement	Faded
Red-white (standard)	White marking**		
Red-white flashing light*			
Red-white constant light			
Black + road surface marking***			
Red-white + road surface marking***			
Red-white diagonal stripes			
Yellow-black diagonal stripes			

Notes: See also Figure 1. Similar conditions (that were compared with each other) are listed in the same column. *The flashing light consisted of a single led light flashing on and off. **The white lines crossed over from one side of the kerb to the other approximately five times per meter. ***The road marking was three white lines in line with the cycling direction in the shape of a triangle pointing towards the bollard.

Figure 1 Conditions in Study 3, (a) (standard) red-white bollard (b) yellow-black bollard (c) black bollard road surface marking (d) kerb with marking (e) grass shoulder



(a) (b) (c) (d) (e)

In addition to the Gecko, two other visual tests were done: the Snellen test (a visual acuity test), and the bow-peri test, a test to measure the extent of the horizontal peripheral visual field. All three tests were completed first with the goggles they would wear during the experiment, and then without the goggles.

3.1.1 Apparatus

A one gear standard Dutch bicycle, with a frame height of 0.56 metre was used.

3.1.2 Procedure

Before the start of the experiment participants had a few minutes to get used to riding the bicycle on the track while wearing the goggles. They were instructed to ride as fast as they considered comfortable and safe, stay within the lines of the track and, where possible, pass obstacles on the right hand side.

Eight locations were used to place the kerb and bollard conditions on the track. The order of these locations was randomly selected and used, in that same order for two participants who rode directly after each other. So each participant encountered an obstacle on location A in the first trial, but the obstacle itself differed for almost every participant. The road markings and shoulder conditions were placed on the same location for every participant, but again the order of the conditions differed for almost all participants. Two participants completed the same course directly after each other so the time spent on changing the obstacles after each course could be reduced with 50%.

The experiment was approved by the Ethical Committee of the Department of Psychology, University of Groningen. Participation took about 1.5 hour per participant. Participants signed an informed consent before the experiment, and received a financial compensation of €15.

3.1.3 Measures

The Dutch version of the rating scale mental effort (RSME, Zijlstra, 1993) was used to assess experienced mental effort. The RSME is a scale with a range of 0–150 with anchor points marked. For example the anchor point ‘little effort’ goes with a score of 26, and the anchor point ‘very great effort’ with a score of 102. An equivalent of this scale was used to measure quality of riding, confidence, visibility, and experienced risk. The adapted risk scale has been used in other studies too (de Waard et al., 2010, in press). After every trial participants were asked to provide ratings on these five measures. After completing all trials were cycled participants also had to complete a questionnaire where they could indicate which of the conditions they preferred.

Participants’ behaviour was also observed by an observer during each trial. The observer was not visible to the participant (hidden by bushes or walls close to the location of the obstacle). The following behaviour was rated: off balance, crossing of lines of the track, braking, passing the obstacle on the wrong (left hand) side, dismounting from the bicycle, touching the road with a foot, and being in contact with the obstacle. If the behaviour did not occur this was rated as 0, if it occurred in a minor way, e.g., slightly out of balance, this was rated as 1, and if it occurred in a major way, e.g., a major steering correction, this was rated as 2. A sum score (with a theoretical maximum of 14) was created. All participants were rated by the same observer.

Speed was derived from GPS position, measured with a Garmin eTrex Legend HXc attached to the handle bars. A text editor was used to cut the GPX data into chunks so it could be opened in GPS utility. This application gave a two dimensional representation of the cycled circuit and computed and presented the speed at each of the locations where the conditions were placed.

The contrast values (expressed in Sobel values) of all stimuli with the background were obtained enabling a ranking on contrast of the conditions listed in Table 1. Photos of the stimuli were taken indoors to control for changing light conditions and allow for relative comparison. The photos were then converted into grey scale and the contrast of the resulting images was reduced in a stepwise fashion using edge detection according to Sobel to determine at which level of contrast the given stimulus (e.g., a bollard) remained visible. A marker with a Michelson's contrast of 0.3 was used to determine the corresponding Sobel value. 0.3 is often advised as a minimum contrast level for the design of the build environment (Wijk, 2008), i.e., conditions that do not meet this criterion can be regarded as poorly visible. Colour is left out of these analyses on purpose, as most objects will be perceived in the periphery of the cyclist's vision. In the periphery and during dusk and darkness (when many accidents happen) the human eye cannot distinguish colours, and therefore the contrast values were determined for these critical conditions. Of course, with focal view colour is important, and therefore the colour of objects is also – to a certain extent – manipulated in the experiment.

3.1.4 Analyses

The effects of the shoulder and road marking conditions were evaluated using a general linear model (GLM) repeated measures test (SPSS for windows, version 16). The two shoulder conditions were compared with each other in one analysis. The same applies to the two road marking conditions, and the three kerb conditions. The bollards were evaluated in one analysis, and post-hoc tests between separate bollard conditions were evaluated using pairwise comparisons with Bonferroni adjustment for multiple comparisons. For ordinal data (observer ratings), a Friedman test was used. If significant, this test was followed by Wilcoxon signed rank test.

Finally, the effect location where the kerbs and bollards were positioned was evaluated. Objects could be positioned on a straight segment, after a curve, or in a curve. The influence of location (irrespective of object) on speed and visibility was tested with a GLM.

3.2 Results

A total of 28 people participated, their average age was 34 years (SD 13.5), 42% of the participants were female. In addition four visually impaired people (who were still cycling) were asked to participate to get an impression of their performance compared with the results of healthy participants who were wearing goggles. All visually impaired participants were male and their average age was 50.4 years. The average contrast sensitivity, visual acuity, and visual field size, measured for the visually healthy participants (with and without goggles) and for the visually impaired participants (without goggles) are shown in Table 2. The visually impaired participants are not included in following analyses, due to the small number and the fact that their visual conditions differed. Table 2 however does show that the visual acuity of the impaired cyclists was comparable to the acuity of the participants wearing goggles. Their contrast sensitivity and visual field size was actually lower than that of the participants wearing goggles.

Table 2 Average results on three visibility tests for the visually healthy participants (with and without goggles) and for visually impaired participants (reference)

	Contrast sensitivity	*Visual acuity*	*Visual field size*
Participants without goggles (*N* = 28)	1.72 log	96%	89.5 degrees
Same participants with goggles (*N* = 28)	0.87 log	30%	87.9 degrees
Visually impaired participants (*N* = 4)	0.58 log	30%	72.5 degrees

Table 3 Contrast of the stimuli with the background expressed in Sobel values

Condition	*Contrast*[1]	*Comment*
Bollards		
Black bollard	84	Exceeded the maximum acceptable score for a Michelson's contrast of 0.3
Yellow-black bollard diagonal stripes	57	
Red-white bollard	45	
Red-white bollard diagonal stripes	40	
Black bollard road surface marking	30	This score just concerns the road surface marking
Red-white bollard road surface marking	30	This score just concerns the road surface marking
Black bollard constant light	1	This score just concerns the light
Red-white bollard constant light	1	This score just concerns the light
Kerbs		
Grey kerb	88	Exceeded the maximum acceptable score for a Michelson's contrast of 0.3
Kerb with markings	25	This score just concerns the lines on the kerb
White kerb	25	
Shoulders		
Grass shoulder	82	
White pavement shoulder	25	
Road marking		
Faded road markings	78	
High contrast road marking	38	

Notes: Note that higher values correspond to lower contrast levels, i.e., to a worsened visibility. [1]A value of 82 corresponds to a Michelson's contrast of 0.3 [Wijk's criterion, see Wijk (2008)].

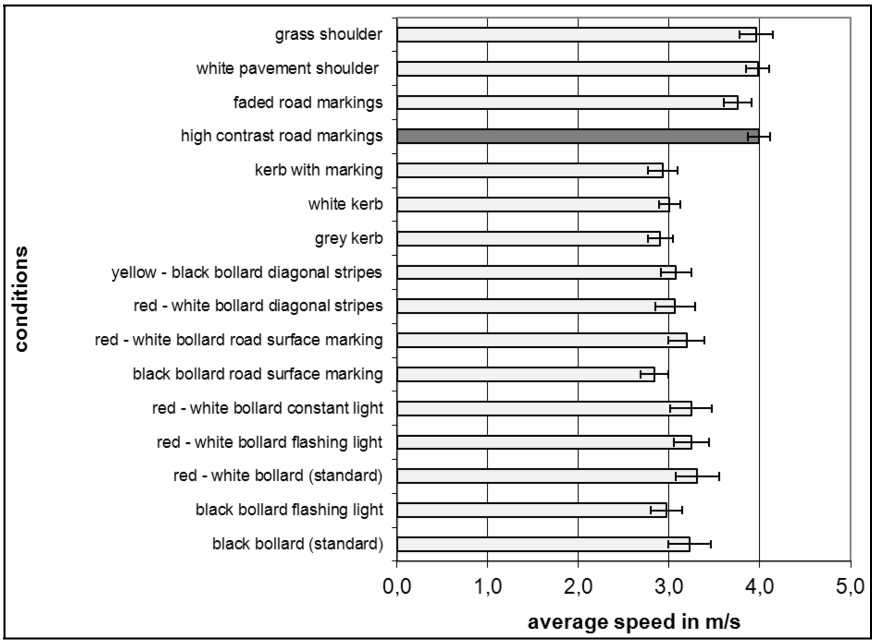
3.2.1 Contrasts

Results with regard to contrast of the objects with the background are shown in Table 3. The black and red-white bollards were only photographed in the constant light condition (a single led light continuously on), not in the flashing light condition (a single led light flashing on and off) as for this analysis this makes no difference. The black bollard and grey kerb had Michelson's contrasts below 0.3, i.e., under Wijk's (2008) criterion for the design of the build environment.

3.2.2 Speed

The GPS speed registration partly failed for two participants. Average speed per condition is depicted in Figure 2. There were no differences in speed between the bollard conditions [*F*(8, 18) < 1, NS], the three kerb conditions [*F*(2, 24) < 1, NS], and the shoulder conditions [*F*(1, 25)< 1, NS]. However, a significant main effect was found for the two road markings conditions in that participants cycled faster when passing high contrast road markings compared with the faded markings [*F*(1, 27) = 4.8, *p* = 0.037].

Figure 2 Average speed per condition

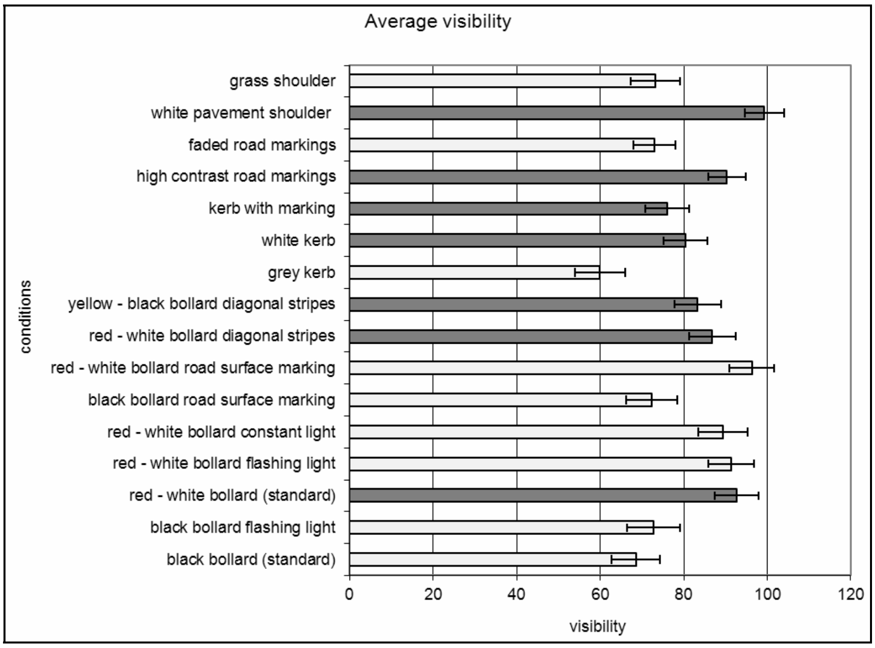


Note: The error bars reflect standard error of the mean.

3.2.3 Ratings

The average ratings of visibility of all conditions are shown in Figure 3. The road markings with high contrast markings were rated as better visible than the faded road marking [*F*(1, 27) = 12.1, *p* = 0.002], the grass shoulder was better visible than the white pavement [*F*(1, 27) = 12.9, *p* = 0.001]. A difference in visibility between the kerbs was also found [*F*(2, 26) = 4.23, *p* = 0.026], the white pavement was better visible than the standard grass shoulder (pairwise comparison Bonferroni adjusted, *p* = 0.02).

Figure 3 Average ratings per condition on visibility on a scale from 0 to 150



Note: The error bars reflect standard error of the mean.

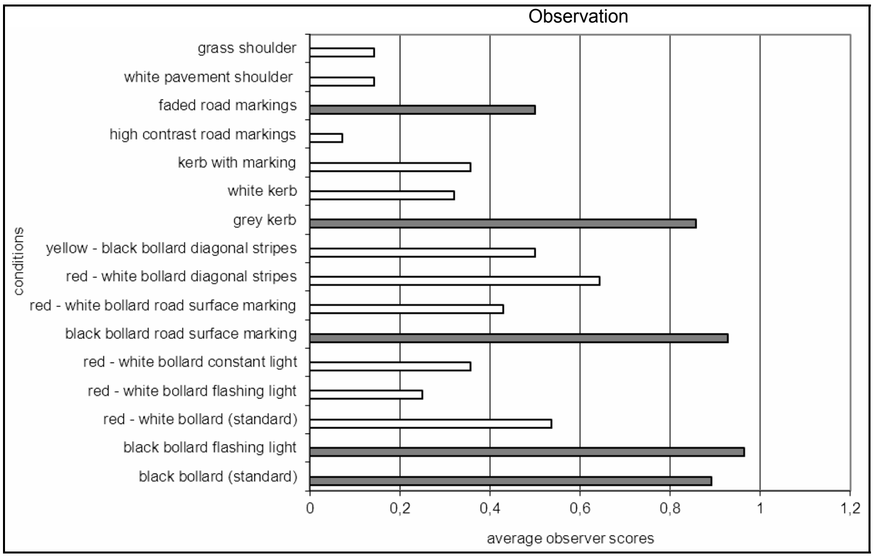
The visibility ratings of the different bollards differed [$F(8, 20) = 5.80$, $p = 0.01$]. Post hoc tests reveal significantly lower ratings for the conditions with black bollards, which differ from the standard red-white (pairwise comparison Bonferroni adjusted, $p < 0.05$). The average rating on visibility for the total of conditions was 81.6 which coincides with a rating in between 'fairly' and 'very visible'.

No significant effects across the different conditions were found for the confidence ratings (average 87.3, 'very confident') risk ratings (average rating 21.5, between 'almost no' and 'a little risk'), riding quality (average rating 89.0, 'I rode well'), and mental effort (RSME, average rating 32.0, between 'a little' and 'some' effort).

3.2.4 Observations

The observed behaviour scores are shown in Figure 4. A high score means that participants had more difficulty cycling in this condition than in conditions with lower scores. Significant effects were found for type of bollard (Friedman test, $\chi^2_{N = 28,\ df = 8} = 37.1$, $p < 0.001$). For example, the black bollard condition led to more unstable cycling behaviour than the red-white bollard condition ($Z = -2.20$, $p = 0.28$). Differences were also found between the three types of kerbs (Friedman test, $\chi^2_{N = 28,\ df = 2} = 9.74$, $p = 0.008$). At the grey kerb significantly more problems were observed (compared with the white and marked kerbs, $Z = -2.56$, $p = 0.010$ and $Z = -2.45$, $p = 0.014$ respectively). Also at the faded roadmarking more problems were observed compared with the high contrast marking (Friedman test, $\chi^2_{N = 28,\ df = 1} = 7.36$, $p = 0.007$), but no difference was found between the two types of road shoulder (Friedman test, $\chi^2_{N = 28,\ df = 1} = 0.67$, NS), see Figure 4.

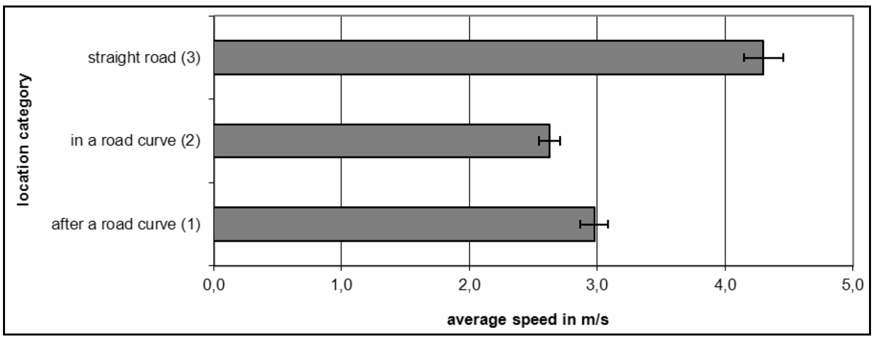
Figure 4 Average observer scores per condition divided by the number of participants (range 0–2)



3.2.5 Location

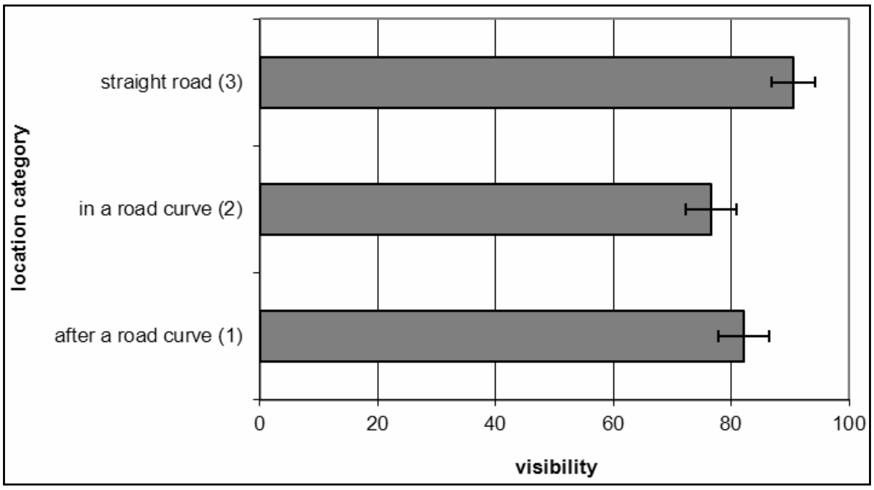
As location can be expected to have an influence on results, speed and visibility scores were also calculated for the different locations, independent of object/condition evaluated at that location. Participants could encounter conditions with kerbs and bollards in three locations; after a road curve (1), in a road curve (2) and on a straight road (3). Participants cycled fastest in conditions where the object was placed on a straight road. Average speed per location is shown in Figure 5. Effects for speed were found for all location categories [$F(2, 25) = 1{,}372$, $p < 0.001$, all pairwise comparisons Bonferroni adjusted, $p \leq 0.017$). Figure 6 shows the average visibility per location category. The conditions with objects on a straight road received the highest visibility ratings [$F(2, 24) = 8.72$, $p = 0.001$, pairwise comparisons Bonferroni adjusted, straight road vs. in curve, $p = 0.003$, and after curve $p = 0.011$].

Figure 5 Average speed per location category



Note: The error bars reflect standard error of the mean

Figure 6 Average visibility rating per location category on a scale from 0 to 150



Note: The error bars reflect standard error of the mean.

3.2.6 Preferences

After participants finished cycling they were asked which conditions they preferred. With regard to bollards, 41% of participants preferred the (common) red-white bollard, 30% preferred the red-white bollard combined with the road surface marking, 11% preferred the red-white bollard with flashing light, 11% preferred yellow-black bollard with diagonal stripes, 3.5% preferred the red-white bollard with diagonal stripes, and 3.5% preferred the black bollard combined with the road surface signs. Nobody expressed a preference for the (also common) black bollard, the black bollard with a flashing light, or for the red-white bollard with the constant light.

Of the kerbs 40% preferred the white kerb, 40% preferred the kerb with marking, and 20% preferred the grey kerb. Of the road markings 100% of the participants preferred the road markings with high contrast. In the shoulder conditions, 85% preferred the white pavement, and 15% preferred the grass.

3.3 Discussion and conclusions Study 3

In Study 3 participants wore goggles to lower their contrast sensitivity and restrict their visual field size in order to mimic seriously reduced vision of a group of older people, who however still can use their bicycle. In general results of the objective contrast measurements coincide with behavioural and subjective results. Red-white bollards are better visible than black ones, and more problems were observed with less conspicuous objects. However, constant lights and flashing lights on bollards did not have the expected positive effect. Rather, the red-white bollards with a constant light and flashing lights were rated similarly on visibility than the red-white bollards without lights. So while lights do appear to improve the objective visibility of the bollards, the subjective visibility is not improved. The reason for the lower visibility scores may lie in the small size of the light (a single led light), and in particular the low luminance of the light in bright daylight conditions. In fact some participants who had cycled in the sun stated they had not seen the lights at all. As such, the objective contrast analyses for the constant lights, as reported in Table 3, are likely to be rather optimistic. However, in adverse weather conditions, or during darkness, favourable results might be expected from these lights because the contrast of a light source will increase as ambient light decreases. A larger or brighter light than used in this study might also have had effect in daylight conditions.

Another remarkable finding was that although relatively few problems were observed in the two road shoulder conditions, while on basis of the contrast measurements the grass shoulder could be expected to be less visible. This might be explained by the mostly sunny weather during the experiment which caused the grass to shimmer, and become more visually distinct.

4 General conclusions

These three studies confirm that visually impaired cyclists appear to experience difficulties when they encounter obstacles in the bicycle infrastructure. Study 1 and 2 showed that older and low vision cyclists report feeling unsafe when they encounter obstacles like bollards, road narrowings, kerbs and shoulders that they view as poorly visible. This is in line with recent research which linked the low visibility of such obstacles, and the course of the road, to the occurrence of single-bicycle crashes (Schepers and Den Brinker, 2011). On the other hand, correlational studies such as the one carried out by Schepers and Den Brinker (2011) are limited when it comes to establishing a causal link between crashes and the visibility of the infrastructure. In an attempt to address this, the experiment in Study 3 included conditions that were based on the findings of Study 1 and 2 with varying levels of visibility. Participants navigated a track containing these different conditions while wearing goggles that decreased contrast sensitivity. Cycling performance and cyclists' feelings of safety while doing so worsened the most in conditions where the visibility of obstacles and the road's course were the poorest. This finding supports the stance that the visual characteristics of bicycle infrastructure are an important factor in single-bicycle crashes.

Several of the findings of this study are important for professionals in the fields of road design and road safety. Firstly, the number of obstacles in the infrastructure should preferably be minimised. However, when a bollard, to prevent other vehicles from entering a cycle path, cannot be avoided the standard red-white bollard is the best choice. Kerbs near bicycle infrastructure should preferably be painted white, as this increases visibility of the object. Similarly, low contrast shoulders reduce the visibility of the road's course and should be avoided. This could be achieved through the use of bright pavements or high-contrast road markings on the edge of the road. These measures are especially important in curves where cyclists have to make a sharp turn.

Furthermore, if obstacles such as bollards are placed at all these should preferably not be located directly after a curve, but on a straight segment and/or several metres away from intersection areas. At the same time, cyclists' expectations should be taken into account (e.g., cyclists may not expect a bollard just in the middle of a long straight cycle track) and given their purpose to keep cars off cycle tracks they should also be visible to drivers (e.g., not too far away from an intersection).

A selection of objects and markings were evaluated in these studies, but only contrast sensitivity was decreased. Future studies could include (simulation of) other visual impairments such as Presbyopia, a visual condition that will affect many, in particular in an ageing society.

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