Accident Analysis and Prevention 74 (2014) 97–106

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Speed choice and mental workload of elderly cyclists on e-bikes in simple and complex traffic situations: A field experiment

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ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 8 October 2014
Accepted 15 October 2014
Available online xxx

Keywords:
Elderly cyclist
E-bike
Mental workload
Speed

ABSTRACT

To study the speed choice and mental workload of elderly cyclists on electrical assisted bicycles (e-bikes) in simple and complex traffic situations compared to these on conventional bicycles, a field experiment was conducted using two instrumented bicycles. These bicycles were identical except for the electric pedal support system. Two groups were compared: elderly cyclists (65 years of age and older) and a reference group of cyclists in middle adulthood (between 30 and 45 years of age). Participants rode a fixed route with a length of approximately 3.5 km on both bicycles in counterbalanced order. The route consisted of secluded bicycle paths and roads in a residential area where cyclist have to share the road with motorized traffic. The straight sections on secluded bicycle paths were classified as simple traffic situations and the intersections in the residential area where participants had to turn left, as complex traffic situations. Speed and mental workload were measured. For the assessment of mental workload the peripheral detection task (PDT) was applied. In simple traffic situations the elderly cyclists rode an average 3.6 km/h faster on the e-bike than on the conventional bicycle. However, in complex traffic situations they rode an average only 1.7 km/h faster on the e-bike than on the conventional bicycle. Except for the fact that the cyclists in middle adulthood rode an average approximately 2.6 km/h faster on both bicycle types and in both traffic conditions, their speed patterns were very similar. The speed of the elderly cyclists on an e-bike was approximately the speed of the cyclists in middle adulthood on a conventional bicycle. For the elderly cyclist and the cyclists in middle adulthood, mental workload did not differ between bicycle type. For both groups, the mental workload was higher in complex traffic situations than in simple traffic situations. Mental workload of the elderly cyclists was somewhat higher than the mental workload of the cyclists in middle adulthood. The relatively high speed of the elderly cyclists on e-bikes in complex traffic situations and their relatively high mental workload in these situations may increase the accident risk of elderly cyclist when they ride on an e-bike.

1. Introduction

According to EU regulations, bicycles with a pedal-assist electric drive system, officially named pedelecs (from pedal electric cycle) but mostly referred to as e-bikes, may supplement human pedalling with no more than 250 W of electric power and only up to a speed of 25 km/h. These e-bikes have become popular, especially among older cyclists. Research shows that the number of injured e-bike cyclists in the Netherlands is increasing, in particular among elderly cyclists (Kruier et al., 2012). This increase is partially the result of more exposure. Not only do more elderly riders purchase an e-bike, when they have one, they also make longer cycle trips and make more trips than on a conventional bicycle (Fietsberaad, 2013). Another possible explanation is an increase in casualty risk (i.e. number of casualties per distance ridden), because of riskier behaviour on an e-bike. Such riskier behaviour might be the higher speeds on e-bikes, especially in complex traffic situations that require fast information processing. The present study was conducted to investigate if in complex traffic situations, elderly cyclists ride faster on an e-bike than on a conventional bicycle and whether their mental workload is higher in these complex traffic situations than in simple traffic situations.

To determine casualty risk, exposure (mostly the annual distance ridden on e-bikes) and the number of casualties are required. To date, no accurate casualty risk figures are available for

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http://dx.doi.org/10.1016/j.aap.2014.10.018
0001-4575/

cyclists on e-bikes in European countries. This is due to the fact that in accident data files often no distinction is made between bicycle accidents and e-bike accidents. Furthermore, most countries do not have accurate exposure data for e-bikes. Data from other sources however suggest that the accident risk of elderly cyclists is higher on an e-bike than on a conventional bicycle. In the Netherlands for instance, an indication of the casualty risk on e-bikes in relation to age can be derived from casualty and exposure data of the 'Spartamet'. The Spartamet was a bicycle with a very small combustion engine which was popular among middle-aged and elderly cyclists in the Nineties of the past century. It was approximately as heavy as today's e-bikes and the combustion engine was approximately as powerful as of the electric engine of today's e-bikes. The maximum speed of the Spartamet also equalled the maximum speed of today's e-bikes (25 km/h). For 25–49 year old Spartamet riders, the casualty risk was approximately the same as for the 25–49 year old cyclists on conventional bicycles. However, for Spartamet riders aged over 50, the casualty risk was about twice that of conventional cyclists of that age (Noordzij and Mulder, 1992; Noordzij, 1993). Recently, the injury risk of e-bikes have tentatively been calculated based on hospital data and estimated mileage from a sample of e-bike data recorders (Fietsberaad, 2013). According to this study, up till an age of 75 injury risk did not differ between bicyclists on an e-bike and bicyclists on a conventional bicycle. However, for cyclists over 75 years of age, the injury risk on e-bikes was twice the injury risk on conventional bicycles. Although, the indications differ regarding the age at which the casualty risk starts to increase, both studies suggest that riding on an e-bike is more risky for elderly cyclists than riding on a conventional bicycle.

Theoretically, several factors can contribute to the presumed higher casualty risk of elderly cyclists on e-bikes. First, e-bikes are an average 10 kg heavier than conventional bicycles. This can make mounting and dismounting problematic, especially for elderly cyclists due to age-related stiffness. In a recent survey among injured e-bikers, Kruier et al. (2012) found that a relative large proportion of e-bikers had fallen while mounting or dismounting their e-bike. Second, elderly who ride on an e-bike may be in poorer physical condition than elderly who ride on a conventional bicycle. For instance, elderly who have ceased cycling on a conventional bicycle may start to cycle again on an e-bike because cycling on an e-bike is physically less demanding. Thereby, comorbidity between diminishing physical strength and diminishing cognitive functions cannot be excluded. McGough et al. (2011) for instance found that for elderly (over 69 years of age), mild cognitive impairment was associated with reduced physical performance. Third, elderly bicyclists may ride faster on an e-bike than on a conventional bicycle. As bicycles offer no protection for cyclists in accidents, it is likely that the faster one rides the more serious the injuries will be in case of a fall or a collision. Higher bicycle speeds may also increase accident risk because of the extra demands on information capacities and on reactions times to sudden events (Aarts and Van Schagen, 2006). In this study, of the three mentioned possible causes that can contribute to casualty risk, we only investigate speed.

To date only few studies on cycling speed on e-bikes have been conducted and none of these studies examined speed behaviour of elderly cyclists. Simons et al. (2009) and Sperlich et al. (2012) for instance examined the relationship between speed choice and physical effort of middle-aged cyclists on an e-bike. When riding on an e-bike, a cyclist can deliver the same amount of biomechanical effort as on a conventional bicycle. Due to the propulsion system, this cyclist rides faster on an e-bike than she or he would have done on a conventional bicycle. A cyclist can also decide to cycle as fast on the e-bike as on a conventional bicycle. This cyclist will use up less biomechanical energy and will become less tired from pedalling. Simons et al. (2009) found that middle aged cyclists (around 50 years of age) did both. They rode an average 3.8 km/h faster on their e-bike when the pedal support was set at its maximum than when the pedal support was switched off. When the pedal support was switched on, participants delivered 15% less physical energy than when the power support was switched off. In the study of Simons et al. (2009) participants only rode on secluded bicycle paths on a terrain with almost no differences in altitude. In the study of Sperlich et al. (2012) participants rode a hilly terrain. Participants in this study (all female, mean age 38) rode an average 2 km/h faster when pedal support was 'switched on' than when it was 'switched off'. In the 'switched on' condition their biomechanical effort was 29% less than in the 'switched off' condition. These two studies show that cyclists in middle adulthood when riding an e-bike, balance speed and physical effort and that this balancing is somewhat different in a hilly terrain than in a flat terrain. These studies are however not about elderly cyclists on e-bikes and are not on balancing of speed and mental effort in simple and complex traffic situations. A limitation of the mentioned two studies is that a comparison was made between switch-on and switch-off conditions on the same e-bike. This does not catch the full difference between the two bicycle types, such as differences in weight and weight distribution. In order to take account of the differences related to weight, in the present study participants cycled on two different bicycles. These two bicycles were geometrically identical, except for the propulsion system. The e-bike had an electric motor and a battery, whereas the conventional bicycle did not.

Cyclists not only balance physical effort and speed, as was studied by Simons et al. (2009) and Sperlich et al. (2012), they presumably also balance mental workload and speed. There is no universally accepted definition of mental workload. De Waard (1996) argues that three interrelated concepts are important. These concepts are task demands, mental workload and effort. Task demands are determined by goals that have to be reached by performance. Mental workload is the result of reaction to task demands; it is the proportion of the mental capacity that is allocated for task performance. Effort is the voluntary mobilisation process of mental resources. He defines mental workload as the "specification of the amount of information processing capacity that is used for task performance" (De Waard 1996; p. 15). With regard to drivers, Cantin et al. (2009) found that for both young drivers and elderly drivers, mental workload increased when the traffic situation got more complex. Although this was true for both groups, it increased disproportionately more for elderly drivers. Other studies found that drivers reduce their speed when the task demands increase (e.g. Alm and Nilsson, 1994; Lansdown et al., 2004). It could be that drivers reduce their speed when they experience too much mental workload (Fuller, 2005). Contrary to car drivers who can drive extremely slow or extremely fast, cyclists have to maintain a minimum speed to prevent them from falling (Kooijman et al., 2011; Schwab and Meijaard, 2013), whereas their maximum speed is limited by their physical energy. To date, no studies are available on how cyclists balance mental work load and cycling speed in relation to the complexity of the cyclist task. We also do not know whether this balancing is the same for all age groups and whether it is different on e-bikes than on conventional bicycles. The aim of the present study is to contribute to the understanding of these processes, thereby addressing the following research questions.

(1) What are the speeds of elderly cyclists ride in simple traffic situations and in complex traffic situations when they ride on a conventional bicycle and when they ride on an e-bike?
(2) Do the speed patterns of elderly cyclists differ from those of cyclists in middle adulthood?

(3) Are there differences in mental workload of elderly cyclists in simple and complex traffic situations when they ride on a conventional bicycle and when they ride on an e-bike?
(4) Do the patterns in mental workload of elderly cyclists differ from the workload patterns of cyclists in middle adulthood?
(5) Is there a relationship between speed and mental workload for elderly cyclists and is this relationship influenced by bicycle type (conventional bicycle or e-bike)?
(6) Do the relationships between speed and mental workload of elderly cyclists differ from the relationships between speed and mental workload of cyclists in middle adulthood?

2. Method

2.1. Participants

Approximately a thousand invitation letters were sent to addresses in the area of The Hague. People could participate if they were either between 30 and 45 years of age (the cyclists in middle adulthood) or if they were 65 years of age or older (the elderly cyclists). Only participants who were in good health and cycled regularly were included. E-bike experience was not required. In total sixty-one participants were recruited. From the sixty-one participants one participant was excluded, as his test was discontinued for safety reasons. Two other participants were omitted, because of sensor failure during the test rides.

The data of the mentioned fifty-eight participants were used in the analyses with regard to speed choice only. The characteristics of this group are presented in Table 1. For the analyses on mental workload, the data from 16 participants had to be excluded. Eight participants were excluded due to technical problems with the equipment that measured mental workload. One participant did not execute the secondary task that was required for the measurement of mental workload. And seven participants failed to execute the secondary task while turning left (the complex traffic situations). Cyclists have to indicate they are about to turn left by extending their left hand. Video footage revealed that these seven participants not only extended their hand before almost all turns to the left but continued extending their hand during parts of the turns to the left. This interfered with the execution of the secondary task, since the left hand of the participants had to be in touch with the handlebar (see Section 2.2). The data from the remaining forty-two participants were analysed with regard to mental workload and the relationship between speed and mental workload. The characteristics of these remaining participants are presented in Table 1.

2.2. Materials and apparatus

The e-bike – a 'Batavus Sorocco Easy' (model with step through frame 2012) with a weight of 27.4 kg and twenty-one gears – had an electric engine located in the hub of the rear wheel and a battery underneath the luggage carrier above the rear wheel, see Fig. 1(a). The electric engine only offered propulsion when the cyclist pedalled and only up to a speed of 25 km/h. Power support could be set in four conditions: no support, low support, normal support and high support. When participants rode on the e-bike, power support was set at 'normal support' and participants were requested not to change this during the test rides. The conventional bike – a 'Batavus Sorocco' (model with step through frame 2012) with a weight of 16.0 kg and twenty-one gears – was technically similar to the e-bike, except for the absence of the electric support, see Fig. 1(b). Participants were requested not to change gears when they were riding on the e-bike because the power supplied by the support system was determined by the force participants put on their pedals. This force changes with gear position and we wanted all participants to have equal amounts of support at certain speeds. They could however change gears when they were riding on the conventional bicycle.

Each bicycle was equipped with a speedometer, GPS, rotation sensor in the bottom bracket, tri-axis accelerometer, steering angle sensor, data storage unit in a box on the luggage carrier and a camera mounted on the end of a pole sticking forward. This camera faced the rider and could capture the entire rider. In the present study, of all the equipment, only data from the speedometer and the camera were analyzed.

Speed was measured with the aid of the dynamo which was embedded in the hub of the front wheel. This speedometer was calibrated on a treadmill. Speed data were logged with a sample rate of 50 Hz. This was done with the computer software MATLAB, running on a small laptop which was located in a box on the luggage carrier.

The riders wore equipment that measured mental workload. Mental workload was measured continuously in order to differentiate between mental workload in complex and simple traffic situations. There are several physiological, subjective, and performance-based methods available to measure mental workload (De Waard, 1996). Physiological methods, such as heart rate, respiratory rate and skin conductance response could not be applied as these measures are strongly influenced by physical workload. Methods based on physiological changes in eye movements such as eye blink rate or electrooculogram (EOG) and brain activities are not appropriate for use in a field setting. Subjective measures such as the NASA Task Load Index Scale (Hill et al., 1992) are useful for deriving information on the work load as experienced by the participants, but less so for a continuous assessment of workload by task complexity (Yeh and Wickens, 1988). Therefore, a performance based method was applied, using the secondary task paradigm. This paradigm is based on the mechanism that the more mental workload is exerted by the primary task, the more the performance on the secondary task will deteriorate (Wang, 2012). A wide range of tasks can be applied as secondary tasks. Its choice mainly depends on the nature of the primary task. When the visual demands of the primary task are high, as is the case when road users drive or ride in traffic, the Peripheral Detection Task (PDT) has shown to be a sensitive measure of mental workload (Van Winsum et al., 1999; Martens and Van Winsum, 2000; Olsson, 2000). This has been demonstrated in car simulator studies (e.g. Van Winsum et al., 1999) and also in real life conditions (e.g. Patten et al., 2006). The PDT is based on the finding that when mental workload increases, the functional visual field shrinks (Miura, 1986). The PDT requires participants to respond as quickly as possible to visual stimuli that are presented at a random signal rate in the peripheral field of view. When the mental workload increases, reaction times get longer and more stimuli will be missed. In the present study, the stimulus was a red LED light that was mounted at the end of a rod, fixed to the

Table 1
Characteristics of the participants in the speed and mental workload analyses.

Age group	Characteristic	Speed analyses	Mental workload analyses
Elderly	*N*	29	21
	Mean age (SD)	69.9 (4.2)	69.5 (4.4.)
	Min–max age	65–79	65–78
	Male	55%	67%
–			
Middle adulthood	*N*	29	21
	Mean age (SD)	37.7 (4.3)	37.3 (4.1.)
	Min–max age	30–45	30–44
	Male	38%	43%

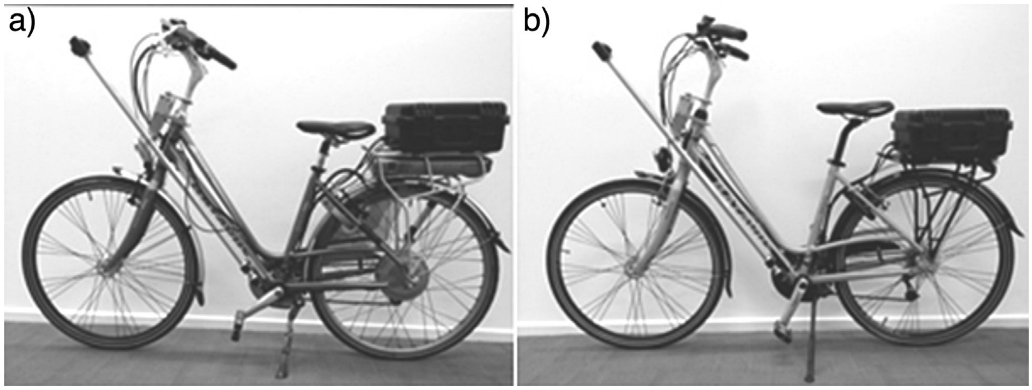

Fig. 1. The instrumented e-bike (a) and the instrumented conventional bicycle (b).

participant's bicycle helmet. As recommended by Van Winsum et al. (1999), this stimulus was presented about 20 cm from the participant's left eye and at a horizontal angle of 11–23 degrees (see Fig. 2).

Reaction times (RTs) were obtained by the use of a push button. This button was attached to the participant's left thumb and could be pressed by pushing this thumb on the bicycle's handlebar. Both, the LED stimulus and push button were connected to a control box, stored in a small backpack. The random signal rate for the PDT was set at an interval of 3–5 s and the LED signal was visible for 1 s. RTs were recorded in milliseconds. A response was recorded as 'missed' if there was no response or a response later than 2 s after the onset of a stimulus. The control box was connected to a rear rack mounted laptop by means of Wi-Fi and data was sampled using Matlab.

As this was a field experiment, exceptional circumstances could have prevented participants from keeping their intended speed or could have prevented them from executing the secondary task due to situations not related to the traffic situation. To detect these exceptional circumstances, so that they could be excluded from the analyses, a GoPro 3 Silver video camera was mounted on the participant's helmet and another GoPro 3 Silver video camera, facing the participant, was mounted on the end of a rod, connected to the bicycle rear frame. This camera captured the entire cyclist from the front (see Fig. 3).

Screen captures from this camera were also used to determine where for a participant a particular section of the route started and ended. This was done with the aid of painted markers on the road surface. The video footage was stored on an SD card in the two cameras and afterwards synchronized with the speed data and PDT data.

Fig. 2. LED light of PDT and camera for forward view.

2.3. The test route

The route, shown in Fig. 4, was approximately 3.5 kilometres long and included a long straight section where the participants

Fig. 3. Screen shot from the camera was mounted on the end of a pole attached to the bicycle rear frame.

Fig. 4. Map of the test route.

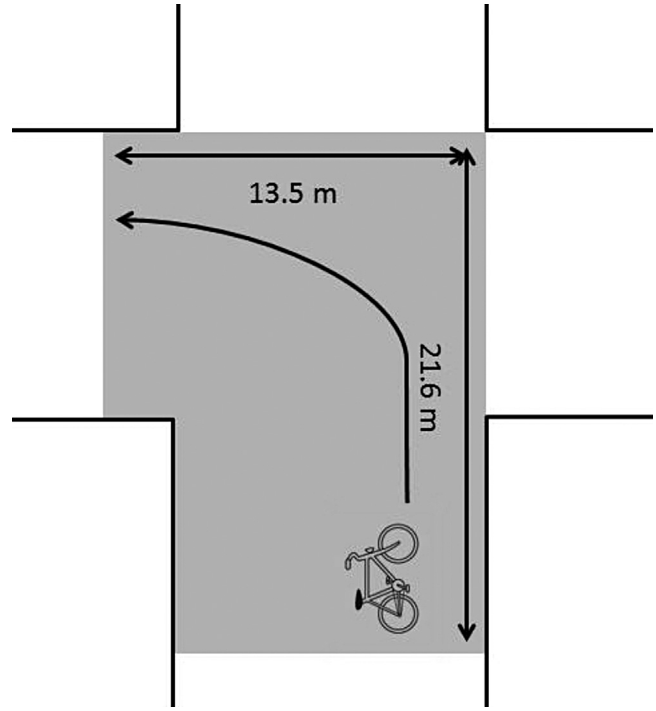

Fig. 5. Area of the left turns in traffic (in grey) which was classified as the area of the complex task.

rode on a secluded bicycle path. This bicycle path is indicated by the white line in the upper left corner of Fig. 4. Participants rode on this seclude bicycle path one time in north-western direction and one time in south-eastern direction. Markings were painted at the beginning and the end of the straight section. This section was approximately 180 m long. The terrain was flat except for a small section where participants had to cycle underneath a railway track. At the farthest point from the starting point (at the upper left corner of Fig. 4), participants had to make a U-turn and cycle back to the starting point (in the lower right corner of Fig. 4).

The route also included a residential area where bicyclists had to share the road with motorized vehicles. In this residential area, participants had to turn four times to the left at intersections. The locations where they had to turn are the other white areas in Fig. 4. At these intersections, a white marking was painted on the road at 21.6 m before the corner and a white marker was painted 13.5 m after the corner (see Fig. 5). Special signposts helped the participants to find their way.

When participants were in the area which is indicated in Fig. 5, they were considered to make a left turn. The left turns at intersections where cyclists had to share the road with motorized traffic, were classified as the complex traffic situations. The mentioned distances before and after the corner were based on the analyses of video footage of the camera that captured the cyclist from the front during trials before the actual test was conducted. It appeared that at approximately 21.6 m before the corner, cyclist tend to stop pedalling for a short moment of time and tend to accelerate slightly at approximately 13.5 m after the corner.

2.4. Procedure

The day before their scheduled test day, participants received a demographic questionnaire to be completed at home, with items on their height, weight and the type of bicycle they use and purpose of their bicycle trips. Upon arrival participants were first informed about details of the study and signed an informed consent form. Thereafter they were equipped with the instruments for the PDT (helmet, push-button and backpack with control box) and their base-line performance on the PDT was measured while they stood next to the bicycle. The participants rode the route four times: a familiarization ride on the e-bike, a test ride on the e-bike, a familiarization ride on the conventional bicycle and a test ride on the conventional bicycle. The order of bicycle type was counter-balanced across participants in each age group. Saddle and steer height were repositioned to suit the participant. During the familiarization rides a researcher rode behind the participant to control for any irregularities and to help in case problems arose. For the test rides, participants got no other instructions than to cycle the predefined route. After the field tests, participants completed a questionnaire about their experiences during the test rides. Participation was rewarded with a 25 gift card.

2.5. Design and analysis

Cycling speed and mental workload of elderly cyclists, on an e-bike and a conventional bicycle was compared to that of cyclists in middle adulthood. Two types of road sections were selected for analysis: complex traffic situations which included left turns at four intersections where motorized traffic could be expected, and simple traffic situations which included two straight sections on a wide secluded bicycle path with almost no other cyclists. A $2 \times 2 \times 2$ mixed design was used, with bicycle type (conventional bicycle and e-bike) and complexity (complex traffic situations versus simple) as within subject factors and age (older cyclist versus cyclist in middle adulthood) as between subjects factor.

Response times (RTs) and the number of hits on the PDT during the four turns to the left (the complex traffic situations) were totalled. The average response times and the percentages of hits (HRs) in complex traffic situations were based on these totals. This was done because turning left only took a couple of seconds. Participants normally received three to four stimuli from the PDT when they were in the area which is depicted in Fig. 4. This is too little for reliable measurement of mental workload for each intersection. Similarly, the RTs and HRs for the two straight sections were totalled before calculating the average RT and HR.

Besides significance of the results, the effect size (Partial eta squared, partial η^2) was considered with partial $\eta^2 \approx .01$ as a small, partial $\eta^2 \approx .06$ as a medium, and partial $\eta^2 \approx .14$ as a large effect size (Cohen, 1988).

3. Results

3.1. Speed

The mean speeds along the route per age group and per bicycle type are shown in Fig. 6.

In the left most and the right most columns in Fig. 6 (Column A and D) were the turns to the left at intersection located (the complex traffic situations). In the two columns directly left and right of the deepest low in the middle of the graph (Column B and C), the participants road on a secluded bicycle path (the simple traffic situations). The deepest low at about 1700 m from the starting point was the turning point in the route. Here participants had to make a U-turn. At the peaks at around 800 m and 2500, participants rode in a tunnel underneath a railway track and just had cycled downslope.

At almost all points along the route, cyclists in middle adulthood on e-bikes had the highest average speed and elderly cyclists on the conventional bicycle the lowest. When cyclists went downhill, and directly thereafter uphill (the highest peaks in Fig. 6), or made a sharp turn (the deepest low in Fig. 6), differences in mean speed per age group and condition (bicycle type) were small. Note that at almost all points along the route, the mean speed of elderly cyclists on an e-bike was about the same as the mean speed of the cyclists in middle adulthood on a conventional bicycle.

Fig. 7 shows the mean speed of the two age groups and the two bicycle types in simple and complex traffic situations. On a conventional bicycle in simple traffic situations, the cyclists in middle adulthood rode an average 19.6 km/h (SD = 2.3) and the elderly cyclists 17.1 km/h (SD = 1.9). On an e-bike in these simple traffic situations, the middle aged cyclists rode an average 23.3 km/h (SD = 2.1) and the elderly cyclists 20.7 km/h (SD = 2.4). The mean speed for the cyclists in middle adulthood on a conventional bicycle in complex traffic situations was 17.7 (SD = 2.1) and for the elderly cyclists 14.9 (SD = 1.7). On an e-bike in these complex traffic situations, the cyclists in middle adulthood rode an average 19.3 km/h (SD = 2.1) and the elderly cyclists 16.6 km/h (SD = 1.8).

The first research question concerned the speed of elderly cyclists, on different bicycle types in relation to the complexity of the traffic situation. A repeated-measure ANOVA with complexity and bicycle type as within-subjects factors, showed that there was a significant main effect of complexity, $F(1,28) = 183.95$, $p < .001$, partial $\eta^2 = .87$, a significant main effect of bicycle type, $F(1,28) = 157.68$, $p < .001$, partial $\eta^2 = .85$, and a significant interaction between 'complexity × bicycle type', $F(1,28) = 70.67$, $p < .001$, partial $\eta^2 = .72$. The results indicate that regardless of bicycle type, elderly cyclists rode slower in complex traffic situations than in simple traffic situations. The results also indicate that regardless the complexity of the traffic situation, elderly cyclists rode significantly faster on an e-bike than on a conventional bicycle. Finally, the interaction effect 'complexity × bicycle type' indicates that although in complex traffic situations, the elderly cyclists rode faster on an e-bike than on a conventional bicycle, compared to their speed in simple traffic situations, on an e-bike they reduced their speed more in complex traffic situations than on a conventional bicycle.

The second question concerned the speed patterns of elderly cyclists compared to those of cyclists in middle adulthood. A repeated-measure ANOVA with complexity and bicycle type as the within-subjects factors and age as between-subject factor resulted in a main effect of age $F(1,56) = 30.53$, $p < .001$, partial $\eta^2 = 35$. Fig. 7 shows that on both bicycle types and in both traffic situations, elderly cyclists approximately 2.5 km/h slower than cyclists in middle adulthood. The interaction effects 'complexity × age', 'bicycle type × age' and 'complexity × bicycle type × age' were not significant. This indicates that in all four conditions, elderly rode at lower speeds than cyclists in middle adulthood, and apart from that, that the speed patterns of elderly cyclists were very similar to those of cyclists in middle adulthood.

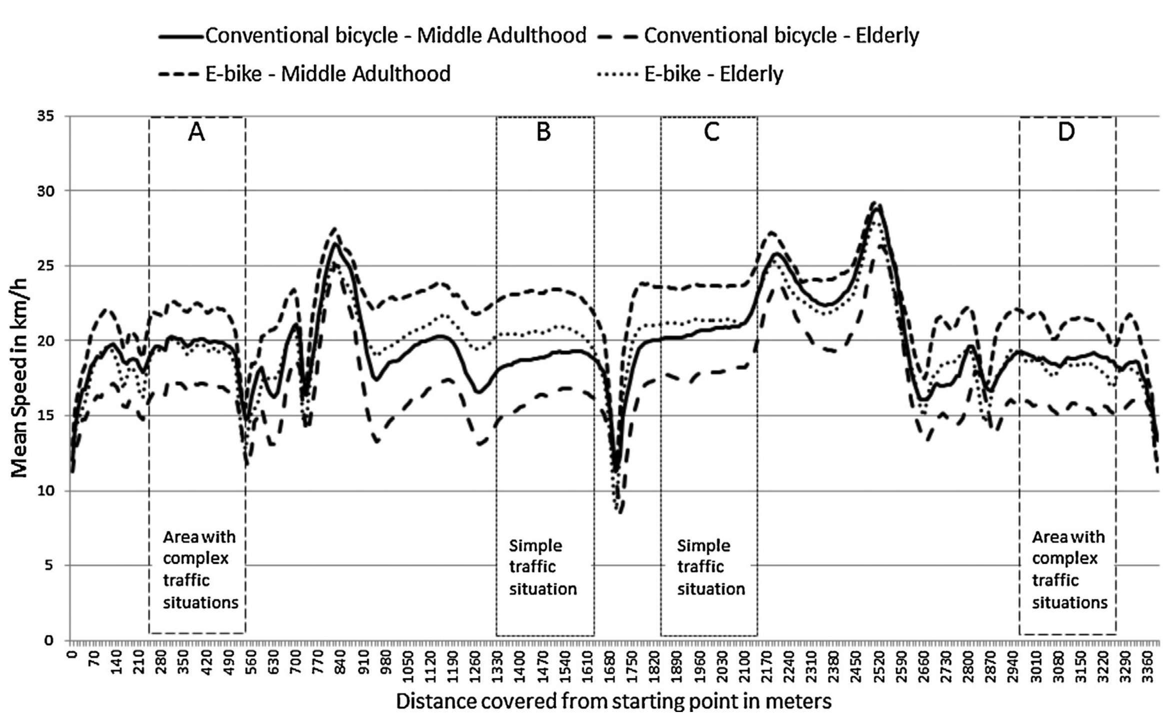

Fig. 6. Mean speed per group and bicycle type at every point in the route.

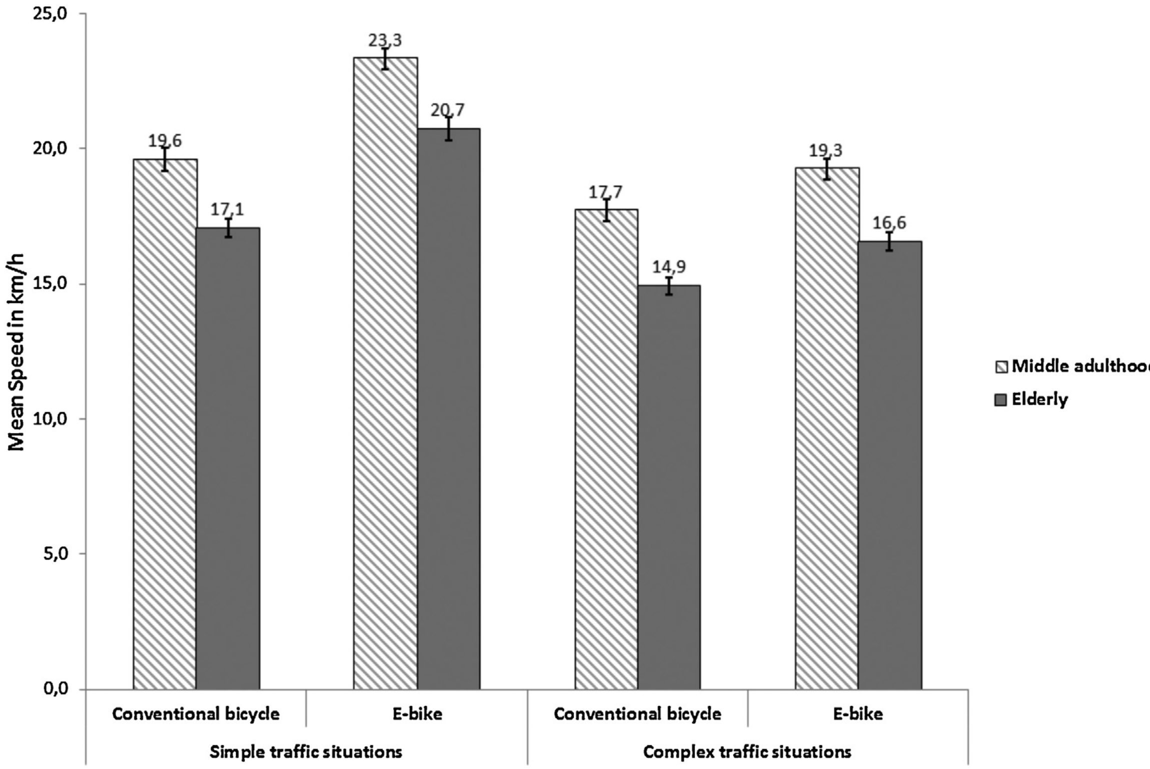

Fig. 7. Mean speed of cyclists in middle adulthood and elderly cyclists on a conventional bike and on an e-bike in simple traffic situations and in complex traffic situations. Error bars present ±1 standard error (SE).

3.2. Mental workload

The third question concerned the mental workload of elderly cyclists on the two bicycle types, in traffic situations that differed in complexity. For mental workload, the PDT generates two different scores: response times (RTs) and hit rates (HRs). RTs and HRs are not completely two sides of the same coin. Normally, mental workload will be considered as high when RT's are long and HR is low. However, in theory a participant can have short RT's and a low HR. In this example, the participant responds fast when a stimulus is detected but detects only a few stimuli. Thus, for an indication of the mental workload, both the RTs and HRs have to be considered. Initial analysis showed that the HRs were not normally distributed. After a square root transformation of the HRs, the criteria for parametric analyses were met. In Table 2 the results on the PDT are presented.

Although the HR-values were transformed, the untransformed HR's are presented in Table 2. This was done to facilitate interpretation. Separate repeated-measure ANOVA's were carried out on RT and HR. Complexity and bicycle type were treated as within-subjects variables. For elderly cyclists, there were no main effects of bicycle type with regard to RTs and HRs. This implies that, regardless of the traffic situation, the RTs and HRs on an e-bike did not differ from those on a conventional bicycle. However, there was a main effect of complexity, both for RTs, $F(1,20) = 26.03$, $p < .001$, partial $\eta^2 = .5$, and for HRs, $F(1,20) = 55.96$, $p < .001$, partial $\eta^2 = .77$. This means that regardless of bicycle type, elderly cyclists had longer RTs and lower HRs in complex traffic situations than in simple traffic situations, which is indicative of a higher mental workload. Neither for RT nor for HR interaction effects were observed with regard to 'complexity × bicycle type'. This indicates that the difference in mental workload in simple and complex situations was not affected by bicycle type.

To examine the possible differences between elderly cyclists and cyclists in middle adulthood, two repeated-measures ANOVA's with complexity and bicycle type as within-subjects factors and age as between-subject factor were carried out. The ANOVA results for the RTs showed a main effect of age $F(1,40) = 14.51$, $p < .001$, partial $\eta^2 = .27$, and for the square root of the HRs, main effect of age was not significant. For RTs and for the square root of the HRs, none

Table 2
Mean response times and hit rate on the peripheral detection task (PDT).

Age group	Bicycle type	Complexity	Mean RT (ms)	SD RT	HR (%)	SD HR
Elderly	Conventional	Simple	536.3	138.8	84.9	16.8
($n = 21$)		Complex	689.8	170.9	69.3	21.9
–						
	E-bike	Simple	546.8	165.8	90.5	14.9
		Complex	663.4	160.2	66.7	24.9
–						
Middle adulthood	Conventional	Simple	445.5	97.0	94.5	10.3
($n = 21$)		Complex	538.7	128.1	83.9	16.6
–						
	E-bike	Simple	446.1	114.1	95.3	8.8
		Complex	494.0	110.4	83.7	14.0

Table 3
Correlations between mean speed and mean response times on the PDT on conventional bicycles and e-bikes in simple traffic situations and complex traffic situations.

Age group	Bicycle type	Traffic situation	r[a]	P
Elderly (n = 21)	Conventional	Simple	−.02	ns
		Complex	−.37	ns
–	E-bike	Simple	−.19	ns
		Complex	−.08	ns
–				
Middle adulthood (n = 21)	Conventional	Simple	−.33	ns
		Complex	−.10	ns
–	E-bike	Simple	−.07	ns
		Complex	−.06	ns
–				
Both groups (n = 42)	Conventional	Simple	−.34	<.05
		Complex	−.44	<.01
–	E-bike	Simple	−.32	<.05
		Complex	−.36	<.05

[a] r = correlation between mean speed and mean RT on PDT.

of the interactions – 'bicycle type × age', 'complexity × age', and 'bicycle type × complexity × age' – were significant. These results indicate that except from the fact that compared to cyclists in middle adulthood, elderly cyclists had longer RTs in all conditions, the workload patterns were quite similar for the two age groups.

3.3. Relationship speed and mental workload

The fifth question concerned the relationship between mental workload and speed choice of elderly cyclist and the influence of bicycle type. The sixth and the last question concerned the possible differences of these relationships between elderly cyclists and cyclists in middle adulthood. As the HRs were not normally distributed, only the interrelationship between RT and speed was explored. Bivariate correlations – presented in Table 3 – were computed to explore the mentioned interrelationships. As shown, correlations were rather weak and only resulted in significant associations when both age groups were combined. The sample sizes were probably too small to generate significant correlations per age group. Note that all correlations were negative. This indicates that higher cycling speeds were associated with shorter RTs and conversely lower cycling speeds with longer RTs.

4. Discussion

The study investigated speed choice and mental workload of healthy elderly cyclists when they cycle on an e-bike. What are their speed choices and mental workloads in simple and complex traffic situations on an e-bike compared to their speed choice and mental workload in these situations on a conventional bicycle? And do their speed choices and mental workloads differ from the speed choices and mental workloads of cyclists in middle adulthood? The elderly cyclists rode faster on the e-bike than on the conventional bicycle. In simple traffic situations they rode an average 3.6 km/h faster on the e-bike than on the conventional bicycle. However, in complex traffic situations they rode an average only 1.7 km/h faster on the e-bike than on the conventional bicycle. The elderly cyclists reduced their speed more in complex traffic situations when they rode on the e-bike than when they rode on the conventional bicycle. Despite this higher reduction in speed, they still had somewhat higher speeds in these complex traffic situations on the e-bike than on the conventional bicycle. Except for the fact that the cyclists in middle adulthood rode an average approximately 2.6 km/h faster on both bicycle types and in both traffic conditions, their speed patterns were very similar to the speed patterns of the elderly cyclists. At almost all points along the 3.5 km long test route, the average speed of the elderly cyclists on an e-bike was approximately the same as the average speed of the cyclists in middle adulthood on a conventional bicycle. Mental workload of the elderly cyclists was approximately the same on both bicycles. Despite the higher speed on an e-bike, the reaction times on the e-bike were not longer and the hit rates not lower than on a conventional bicycle. Their mental workload on both bicycle types was higher in complex than in simple traffic situations. Thus, although the elderly cyclists reduced their speed in complex traffic situations on both bicycle types, they still experienced a higher mental workload in these situations. The cyclists in middle adulthood had shorter reaction times than the elderly cyclists on both bicycle types and in both traffic situations. However, the hit rates of the cyclists in middle adulthood did not differ significantly from the hit rates of the elderly cyclists. This indicates that the mental workload of the elderly cyclists was somewhat higher than the mental workload of the cyclists in middle adulthood on both bicycle types and in both traffic situations.

The speed patterns of elderly cyclists on e-bikes may have various effects on road safety. If it becomes the case that most elderly cyclists choose an e-bike and other age groups mainly remain cycling on conventional bicycles, cycling speeds will become more homogeneous. This may result in fewer bicycle–bicycle crashes. Benefits for road safety may also be the higher speed on e-bikes. Keeping balance takes less rider control effort at higher speeds (Kooijman and Schwab, 2013; Schwab and Meijaard, 2013). Higher speeds and faster acceleration will also reduce exposure to dangerous situations. It for instance will reduce the time to cross an intersection. Negative safety effects are however also possible. Lateral sway increases quadratic with forward speed, so cyclists need more lateral space at higher speeds (Meijaard et al., 2007). At higher speeds injuries will also become more severe in case of a fall or a collision, and the available time to react to unexpected events will be shorter (Aarts and Van Schagen, 2006). Moreover, the complex traffic situations in this study were turns to the left at intersections where cyclists have to share the road with motorized vehicles. Elderly cyclists experienced a higher mental workload during these turns to the left than when they cycled on a secluded bicycle path (the simple traffic situation). Goldenbeld (1992) analyzed crash reports of elderly cyclists. He found that most crashes between elderly cyclists and cars occurred at intersections without traffic lights and that in about a quarter of these crashes the elderly cyclist turned left. The higher mental workload during turns to the left may have contributed to these crashes. Because in the complex traffic situations, the elderly cyclists had a somewhat higher speed and not a lower mental workload when they cycled on an e-bike, their crash risk on an e-bike in complex traffic situations may be higher than it already is on a conventional bicycle.

Studies on elderly car drivers showed similar results of complexity on mental work load. For instance, Cantin et al. (2009) found that elderly car drivers and young car drivers experienced a higher mental workload in complex traffic situations than in simple traffic situations. However, in contrast to the present study, Cantin et al. found that elderly drivers had a disproportionately higher mental workload in complex traffic situations. It is not clear why in contrast to elderly drivers, in the present study no disproportionately higher mental workload was found for elderly cyclists in complex traffic situations. It is possible that the driving task is cognitively more demanding than the cycling task. Due to the higher speeds of cars, traffic situations change more rapidly, which requires fast information processing. Therefore, mental workload may be higher for drivers than for cyclists. The extra effect of task complexity on mental workload for elderly road users may not show up when mental workload in complex traffic situations is still relatively low.

It was hypothesized that cyclists would reduce speed when task demands increase. This hypothesis was based on the patterns previously observed among car drivers (e.g. Alm and Nilsson, 1994; Lansdown et al., 2004). The results showed that regardless of bicycle type, cyclists in both age groups indeed rode slower in complex traffic situations. However, within the simple traffic situations and within the complex traffic situations, higher speeds were also associated with faster reaction times. This was only true when both age groups were combined. For car drivers an opposite association has been found. Patten et al. (2004) found that higher speeds of car drivers were associated with longer reaction times. A study about the role exercise on cognitive performance in relation physical condition could explain this contradiction. Brisswalter et al. (1997) found that during exercise, physically fitter persons had shorter reaction times in a simple reaction time test. Thus, physically fitter cyclists may ride faster and also perform better on the PDT than physically less fit cyclists.

A field experiment as applied in this study has strong points and some weaknesses. In terms of its strengths; the present study is one of the first studies that aimed to explore the characteristics of cycling on the open road while speed and mental workload were continuously measured. Study design and the instrumentation were derived from studies on car drivers. This study demonstrated that study design and instruments for cars and car drivers can be used for cyclists and bicycles. This study however also showed that cyclist behaviour is different from driver behaviour and that what is found for car drivers cannot simply be generalized to bicyclists. Special studies with bicyclists are necessary to understand cyclist behaviour.

The most important limitation of the field experiment is that it is an experiment with particular participants. All elderly cyclists in the study were healthy and still cycled regularly on a conventional bicycle. They did not need an e-bike because they were physically not any longer able to cycle on a conventional bicycle. Consequently, the results may not be valid for the many cyclists who choose to use e-bikes because of a deteriorating health or loss of muscle strength. A further limitation concerns the response method for measuring mental workload. Participants had to press a button with their left hand, by pushing it on the handlebar. This response method interfered with the execution of the cycling task, as participants also used this hand to indicate their intention to turn left. We piloted a few alternative methods, but could not find a more satisfactory one without jeopardizing the standardized PDT method. So far, no alternative response method could be developed. Another limitation was the selection of the complex traffic situations. These were intersections without bicycle lanes were cyclists had to turn left. All four intersections were located in a residential area. Turning left in situations where the traffic volume is low, are not very complex. However, the traffic volume in this residential area was slightly higher than normal because of the of an adjacent shopping center and hospital. One should also be aware of the fact that even when the traffic intensity is rather low, bicyclists always have to check in all directions if no traffic is approaching the intersection. The intersections with real high traffic volumes in the vicinity of the test route were all regulated with traffic lights and had bicycle lanes. They therefore were not complex for cyclists. Would there have been intersections with high traffic volumes without traffic lights, we would not have included them in the test route because this would have put participants too much at risk. The only safe way to investigate cyclists behaviour in real complex traffic situations probably is in a bicycling simulator.

There are several areas that could be explored and call for further study. First, there are studies about physical effort and speed on e-bikes (Simons et al., 2009; Sperlich et al., 2012) and the present study is about mental effort and speed on e-bikes. There are however no studies in which the relationships between physical effort, mental effort and speed on e-bikes are explored. Fatigue for instance might moderate speed and mental work. Second, a better understanding is needed of what constitutes complexity in a cycling task. There may be differences because of control differences. Where the car is always laterally stable, the bicycle, being a single-track vehicle, is in constant need of control in order not to fall over. The main instrument to keep balance is steering (Moore et al., 2011). This steering for balance can interfere with steering for manoeuvre around. It could be that in the complex traffic situations speeds were not only lower and mental workloads were not only higher because of task demands at the tactical level (e.g. searching for approaching vehicles before and while turning left) but also because of task demands at the operational level (e.g. keeping balance when executing a turn). It cannot be excluded that executing the turn itself may have influenced speed and mental workload apart from the experienced task demands at the tactical level. Finally, trip conditions may differ and affect the choice for e-bike riding. Therefore additional studies need to be carried out to observe the behaviour of e-bike riders in natural conditions.

Acknowledgements

This study was facilitated by the Dutch Ministry of Infrastructure and Environment. The authors would like to thank Jodi Kooijman, Thom van Beek and Nick Appelman for designing and building the instrumented bicycles. They would also like to thank Richard van der Horst and Ingmar Stel of TNO for making the PDT suitable for bicycles. Finally, the authors would like to acknowledge the voluntary contribution of all the participants in the research.

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