

Cycling Safe and Sound

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Summary

Cycling safety is a major traffic safety issue both in the Netherlands and abroad. The number of cyclist fatalities in the EU has been decreasing in recent years, however at a slower rate than those of car occupants or pedestrians.

One of the factors negatively influencing cycling safety may be related to limitations on availability of auditory cues. Auditory cues, such as tire and engine noises can provide important information about the presence and location of approaching traffic.

Recently two trends have raised concerns about the use of auditory cues by cyclists. One is the growing popularity of electronic devices, mainly mobile phones, which are used by cyclists to listen to music or to have a conversation. The other trend concerns the increasing number of (hybrid) electric cars, which are generally quieter than conventional cars. This thesis addresses the concerns regarding these two trends.

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Agnieszka Stelling-Kończak

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The impact of quiet electric cars, listening to music
and conversing on the phone on cyclists'
auditory perception and cycling safety

Agnieszka Stelling-Kończak

Cycling Safe and Sound

Proefschrift

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Preface

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1. General introduction

Cycling offers important benefits, such as improved health and affordable mobility, while reducing negative effects of transportation in terms of environmental pollution, noise and roadway congestion. Cycling is therefore strongly encouraged by governmental policies of many countries and it is expected to become a central part of the mobility solutions in many cities. Although society and individuals may benefit from widespread bicycle use, cycling is not without risks. Cyclists are vulnerable road users. Crashes with a motorized vehicle are especially severe for cyclists, since their mass, velocity and level of protection is much lower than that of car or other vehicle occupants. Furthermore, recent EU-wide developments indicate that cyclists have been benefitting less from safety improvements reducing the overall number of road fatalities. The number of fatalities among cyclists across the EU in the past fifteen years was decreasing at a slower rate than those of vehicle occupants or pedestrians (see also *Section 1.1*).

Given the cycling promotion efforts and the negative trends in cycling safety in many European countries, there is a significant need to address cycling problem areas and to identify potential future threats for cycling safety. One of such potential threats is limited availability of auditory information caused by two recent trends: 1) the growing number of quiet electric and hybrid¹ cars on the road and 2) the proliferation of portable electronic media devices, currently predominantly smartphones, used to make a phone call or to listen to music, also when in traffic. Both trends have recently generated concerns about and interest in the use of auditory cues by cyclists.

Safe navigation through the traffic environment relies heavily on visual perception (see, e.g. Owsley & McGwin, 2010; Schepers et al., 2013). For cyclists visual information is not only important for the monitoring of traffic hazards, but also for keeping balance (Mäkelä et al., 2015). Although visual information is essential, traffic sounds can also serve as important cues for

¹ The term 'hybrid electric cars' is used in this study to refer to cars which are driven either exclusively or partially in electric mode i.e. fully electric cars and hybrid electric cars of various types.

road users. Auditory information can act as an attentional trigger and can facilitate detection and localisation of relevant sound sources. The sound of a honking horn, an ambulance or police siren, can often be heard before the cars emitting these sounds can be seen. While for all road users it is important to perceive those loud traffic sounds, for cyclists, less prominent traffic sounds, such as pavement, tire and engine noises may also be used as meaningful signals.

Cyclists may benefit from, or in some instances even depend on traffic-related sounds. Contrary to the visual information, auditory information is omnidirectional, i.e. it does not require the listener to attend to a particular spatial location nor to be oriented in any specific direction to perceive a sound. Therefore auditory perception may be especially important for cyclists for gathering information about approaching traffic from areas outside one's field of view, or when visibility is obstructed (Ashmead et al., 2012; Barton, Ulrich & Lew, 2012; Mori & Mizohata, 1995).

Listening to music or talking on the phone while cycling as well as the growing number of quiet electric cars on the road can make the use of auditory cues challenging for cyclists. Cyclists may simply not hear electric cars approaching on time, which can lead to unsafe situations. Global sales of electric vehicles² almost doubled between 2014 and 2015 and (OECD/IEA, 2016) reaching 1.26 million of electric cars in 2015. The number of electric vehicles is expected to increase sharply as many European countries have set ambitious sales or stock targets for electric cars in the near future (IEA/EVI, 2013). The Netherlands, for example, aims to have 200,000 electrically powered cars in 2020 and one million in 2025 (IEA, 2012).

Listening to music or conversing on the phone may mask traffic sounds or divert cyclists' attention away from the traffic task. As a result auditory cues available for cyclists to assess the presence, proximity and localisation of approaching traffic may be reduced posing a safety hazard. Many cyclists, especially youngsters, listen to music or have a phone call. Recent observational studies in the Netherlands show that about 17-23% of cyclists use a cell phone: up to 2% of cyclists make a phone call, 2-4% operate the screen (texting and searching for information) and 15-16% listen to music whilst cycling (Broeks & Zengerink, 2016; Broeks & Zengerink, 2017; De Groot-Mesken, 2015; De Waard, Westerhuis & Lewis-Evans, 2015). Young cyclists

² i.e. battery electric and plug-in hybrid electric vehicles

aged 12-17 and 18-25 were more frequent users of a mobile phone than older age groups as well as cyclists younger than 12 years old³ (Broeks & Zengerink, 2017). These results are in line with a recent Dutch survey showing that the use of a mobile phone is most popular among cyclists in age younger groups, that is 12-17, 18-25 and 25-34 years old⁴ (Christoph, Van der Kint & Wesseling, 2017).

In response to the concerns regarding the quietness of electric cars and cyclists using electronic devices, a number of developments have been initiated in various countries. To start with, some countries have introduced a ban on listening to music or talking on the phone while cycling (Germany and in some states of the USA). Next, various government agencies (e.g. in Japan, the USA, Europe) are working on standards for a minimum sound level emitted by vehicles (European Commission, 2014; NHTSA, 2018). Furthermore, technological solutions are being developed, such as detection systems warning drivers for approaching cyclist or special headphones allowing cyclists to hear the surroundings together with music. However, fundamental knowledge about cyclists' use of auditory information on which these initiatives should be based is very limited (for a more detailed description of the research gaps see *Chapter 2*). Therefore, the question arises whether these are the necessary and right countermeasures to protect cyclists and to improve cycling safety. Before describing the focus of this thesis in more detail, we will first provide an overview of trends in cycling safety as some of these trends have influenced the focus of the thesis.

1.1. Cycling safety

Cycling safety is a major traffic safety issue both in the Netherlands and abroad. More than 2,000 cyclists were killed in road crashes in the EU-countries in 2015, which constitutes 8% of the total number of road fatalities (European Commission, 2017a). The share of cyclist fatalities out of the total number of road deaths differs between countries. The Netherlands has the highest share in the EU-countries: in 2015 20% of road fatalities and 63% of seriously injured crash victims were cyclists (Korving et al., 2016).

Cyclists in the EU benefit less from the safety improvements that have contributed to the overall reduction in the number of traffic fatalities (NHTSA,

³ Age of cyclists was estimated.

⁴ Cyclists younger than 12 years old did not participate in the study.

2012; Steriu, 2012). Figure 1.1 shows that the number of fatalities among cyclists across the EU was decreasing between 2006 and 2015, however at a slower rate than those of vehicle occupants or pedestrians (see Figure 1.1). A reduction in the number of fatalities reached 27% for cyclists versus 35% for pedestrians and 44% for car occupants and. In the same period in the Netherlands, the number of fatalities among car occupants decreased with 35%, while a reduction of only 14% was recorded for cyclists (Korving et al., 2016).

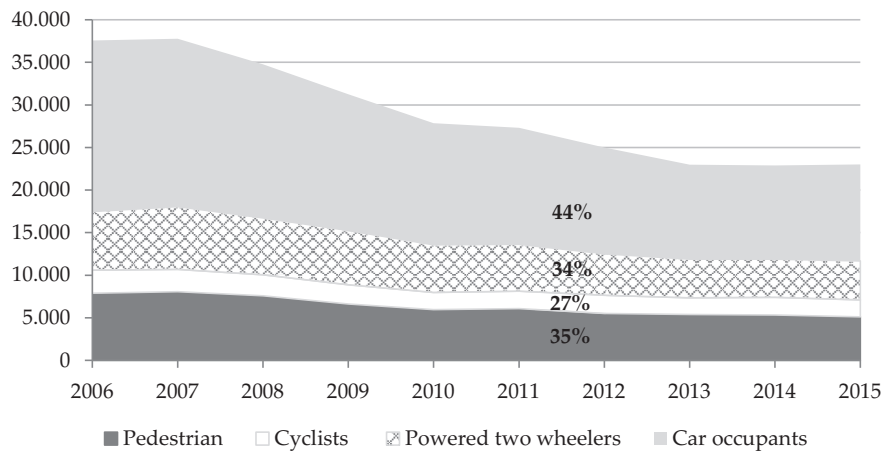


Figure 1.1. Road deaths between 2006 and 2015 in EU-25 by road user (European Commission, 2017b).

1.1.1. Risk

A good indicator of the trends in cycling safety is the fatality risk, which is the number of cyclist deaths per unit of exposure e.g. distance travelled. However, only a few countries in Europe collect data on the number of kilometres cycled. This data is not in all these countries updated yearly. Cyclist fatality risk decreased between 2001 and 2009 in the countries which collect exposure data, however only in Denmark was the decrease substantial and to a very low level (from 19.6 to 8.5 cyclist deaths per billion kilometres cycled). In other countries, the reduction of fatality risk was either very slight (Norway: from 11.5 to 11), or the risk remained relatively high (Great Britain; from 33.1 to 21) (OECD/ITF, 2013; Steriu, 2012). In the Netherlands there was a reduction of 30%, from 17.3 to 12.3 cyclist deaths per billion kilometres cycled (Steriu, 2012). However, since 2009 there has been practically no further reduction of cyclist fatality risk in the Netherlands (Goldenbeld et al., 2017). Furthermore, over the

period of 2001 and 2009, the risk of serious injury for cyclists actually increased. Due to underreporting, the risk of serious injury for cyclists in the Netherlands for more recent years could not be determined (De Groot-Mesken, Duivenvoorden & Goldenbeld, 2015).

1.1.2. Age groups

A significant number of overall casualties in Europe are the elderly. Cyclists over 65 years old constitute 44% of all cyclist fatalities across the EU- countries (European Commission, 2017a). *Figure 1.2* shows a great spike in fatalities among those 65 years and older. The high fatality rate of the elderly has been related to age-related declines in sensory and cognitive functions (Davidse, 2007). In addition, due to frailty associated with aging, the elderly run a relatively high risk of dying or sustaining serious injuries as a result of a cycling crash (Davidse, 2007; Evans, 2001).

Besides the elderly, teenage cyclists are a concern. As can be seen in *Figure 1.2* there is a local peak in cyclist fatalities among teenagers aged between 14 and 18. At this age, youngsters are likely to increase their cycling autonomy. The peak in fatalities may be related to a higher number of kilometres cycled by teenagers. However, a higher frequency of risky behaviour among this age group may also play a role. Due to their physical and mental development, young adolescents are attracted to risky challenges, they are more susceptible to peer pressure, and they have less self-control and overview than older adolescents.

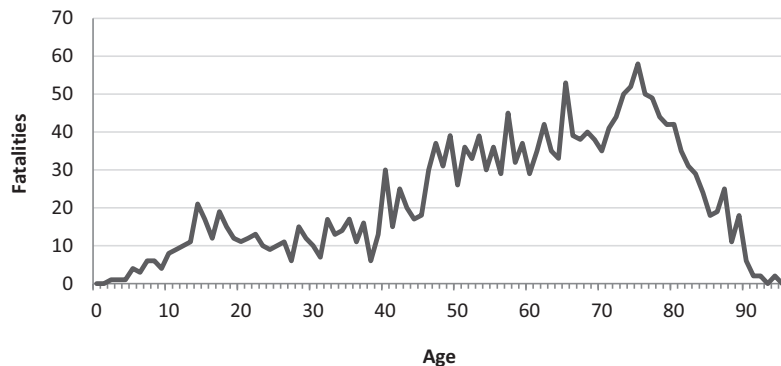


Figure 1.2. Cyclist fatalities by age in EU countries in 2014.

Source: CARE Database, May 2016 (European Commission, 2017a).

No data is available over cyclist fatality risk by age group in the EU-countries. In the Netherlands, older cyclists have the highest fatality risk. The fatality risk increases significantly for cyclists aged 60 years old and above, and it is the highest for cyclists aged 80 years and above. The fatality risk of teenage cyclists is lower than that of older cyclists. However, cyclists aged 15-19 years have a higher fatality risk than cyclists up to 15 years old or those aged 20-49 years.

1.2. Focus of this dissertation

Cycling is strongly encouraged by governmental policies of many countries (OECD/ITF, 2013) and it is expected to become a central part of the mobility solution in many cities. It is therefore important to identify and address factors that negatively influence cycling safety. One of such factors may be cyclists' restricted auditory perception. This dissertation aims to investigate the extent to which restricted auditory perception influences cycling safety. To accomplish the aim, the following research questions have been studied throughout the thesis:

1. To what extent does listening to music and conversing on the phone impact cycling safety?
2. To what extent do acoustic properties of electric (hybrid) electric cars pose a safety hazard for cyclists?

As stated in *Section 1.1*, older and teenage cyclists are particularly vulnerable from the perspective of cycling safety. Therefore, this thesis focuses on these age groups - specifically on cyclists aged 16 to 18 and 65 to 70. Teenagers and the elderly are also of interest from the perspective of the auditory perception of traffic sounds: the former due their frequent use of devices and the latter due to decline in hearing abilities in old age (e.g. Schieber & Baldwin, 1996; Van Eyken, Van Camp & Van Laer, 2007). Additionally, a third age group, i.e. cyclists in middle adulthood (30-40 years old), was included to serve as a reference for the other two age groups.

1.3. Theory and methods

Numerous driver behaviour models have been developed, but a specific conceptual model incorporating the impact of auditory information on traffic safety is lacking. Therefore, *Chapter 2* introduces a conceptual model of the role of auditory information in cycling that has been the theoretical basis for the

empirical studies reported in *Chapter 3, 4* and *5*. This integrated model combines the information processing models (Endsley, 1995; Shinar, 2007; Wickens et al., 2004), general driver behaviour models (Fuller, 2005; Hurts, Angell & Perez, 2011) and insights from research in applied auditory cognition (Baldwin, 2012). For a detailed description of the model see Section 2.2.

Research findings presented in this thesis are based on different methods; i.e. a literature review and crash data analysis (*Chapter 2*), a laboratory study (*Chapter 3*), a survey (*Chapter 4*) and a field study in real traffic (*Chapter 5*).

1.4. Outline

The dissertation consists of six chapters divided in three main parts:

1) problem definition (*Chapter 1* and *2*), 2) empirical studies (*Chapter 3, 4* and *5*) and 3) conclusions and reflection (*Chapter 6*). This structure is depicted in *Figure 1.3*. *Chapters 2, 3, 4* and *5* were previously published as articles in peer-reviewed journals.

Chapter 2 presents a review of current knowledge about the use of electronic devices and the acoustic characteristics of (hybrid) electric cars in relation to cycling safety. To this end, two sources of information are used: literature and crash databases. This chapter also identifies knowledge gaps that need to be addressed for a better understanding of the role of auditory perception in cycling safety.

Chapters 3, 4 and *5* describe empirical research carried out during this PhD-project to address some of these knowledge gaps. *Chapter 3* presents the results of a laboratory study into the auditory localisation of electric and conventional cars. The study includes vehicle motion paths relevant for cycling activity and identifies problematic areas in the localisation of car sounds.

Chapter 4 investigates the impact of listening to music, talking on the phone while cycling and the sound emission of electric cars on cycling safety by presenting the results of an Internet survey among cyclists. The survey explores possible contributions of quiet vehicles, listening to music and phoning while cycling to safety-related incidents. It also describes self-reported compensatory behaviours of cyclists who listen to music or talk on their mobile phones, such as increasing visual attention or decreasing cycle speed.

Chapter 5 explores more closely the visual attention of cyclists while listening to music. Self-reported data used in the previous chapter could not provide quantitative evidence on the location and duration of cyclists' visual effort. Therefore, *Chapter 5* presents a study in real traffic in which a head-mounted eye-tracker was used to monitor cyclists' glance behaviour. The study explores whether cyclists listening to music compensate for the limited auditory input by increasing their visual attention. It also evaluates the suitability of a naturalistic approach to answer this research question. Additionally, the study presents ethical dilemmas related to performing research in real traffic.

Finally, *Chapter 6* discusses the main findings of this thesis and their implications. This chapter also suggests a few areas for future research.

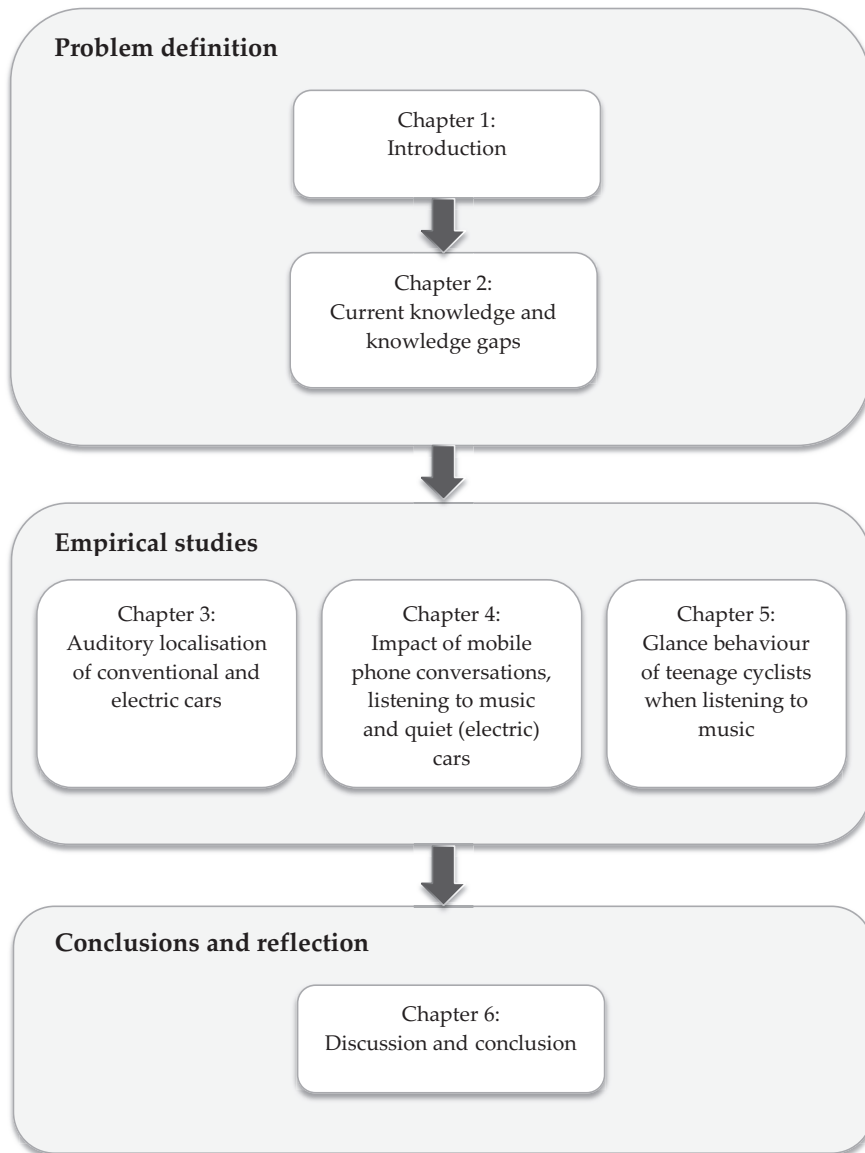


Figure 1.3. The structure of the dissertation.

2. Current knowledge and knowledge gaps: literature review and crash data analysis ⁵

As mentioned in the previous chapter, the popularity of portable devices and the quietness of electric cars have generated interest in and concerns about the use of auditory cues by road users. This chapter consolidates current knowledge about listening to music, conversing on the phone and acoustic properties of electric cars in relation to cycling safety. To this end, both a literature review and a crash data analysis are carried out. The Dutch crash data involving cyclists is used to investigate whether and to what extent, the quietness of a car and cyclists' use of electronic devices are factors contributing to crashes. The literature review investigates crash involvement, behavioural effects of listening to music or phoning, detectability and localisation of (hybrid) electric cars and experiences of drivers of (hybrid) electric cars. Since relevant studies with cyclists are scarce, the literature review includes also studies with pedestrians.

Section 2.1 presents the rationale for the study. The methods adopted for the literature review and the crash data analysis are described in *Section 2.4*. In *Section 2.5* the research findings regarding both the literature review and the crash data analysis are presented. First, the results concerning the use of devices by cyclists and pedestrians are reported, followed by the results regarding hybrid and electric cars. The research findings are presented in relation to a conceptual model, which is proposed in *Section 2.2*. The model is also used in *Section 2.6* to identify the most important knowledge gaps and to provide recommendations for future research. *Section 2.7* discusses the main findings and their implications and, finally, *Section 2.8* provides conclusions.

⁵ This chapter was first published in Transport Reviews: Stelling-Kończak, A., Hagenzieker, M., Van Wee, G.P. 2015. *Traffic sounds and cycling safety: The use of electronic devices by cyclists and the quietness of hybrid and electric cars*. Transport Reviews, vol. 35, nr. 4, p. 422-444. Note: The layout, section numbers and reference style of the articles presented in *Chapter 2*, *3*, *4*, and *5* may differ from the versions published in the journals.

ABSTRACT The growing popularity of electric devices and the increasing number of hybrid and electric cars have recently raised concerns about the use of auditory signals by vulnerable road users. This paper consolidates current knowledge about the two trends in relation to cycling safety. Both a literature review and a crash data analysis were carried out. Based on a proposed conceptual model, knowledge gaps are identified that need to be addressed for a better understanding of the relation between limitations on auditory information while cycling. Results suggest that the concerns regarding the use of electronic devices while cycling and the advent of hybrid and electric vehicles are justified. Listening to music and conversing on the phone negatively influence cyclists' auditory perception, self-reported crash risk and cycling performance. With regard to electric cars, a recurring problem is their quietness at low speeds. Implications of these findings in terms of cycling safety are discussed.

2.1. Introduction

Noise emission is one of the main negative environmental impacts from road transport. Road traffic noise disturbs sleep, impairs school performance and leads to emotional annoyance (Stansfeld & Matheson, 2003). However, in some instances, cyclists and pedestrians (especially the visually impaired), presumably rely on or even depend on traffic-related sounds such as pavement, tyre and engine noises (see e.g. Guth, Hill & Rieser, 1989). Therefore, eliminating the source of traffic noise might pose a safety hazard for these road users.

Recently, the rising number of quiet (hybrid) electric cars on the road and the preoccupation with portable electronic media devices among road users, generated interest in and concerns about the use of auditory signals by cyclists and pedestrians. Global sales of electric vehicles more than doubled between 2011 and 2012 (IEA/EVI, 2013) and many European countries aim to increase the number of electric cars significantly in the near future (IEA, 2012). As for electronic devices, for example, in the Netherlands, 48% of the cyclists listen to music while 58% engage in a phone call (Goldenbeld, Houtenbos & Ehlers, 2010; Goldenbeld et al., 2012).

How road users use auditory information to detect and localise approaching cars has only recently become the subject of empirical investigation. Studies in this field have mainly focused on the importance of auditory cues for pedestrian safety. Up until now there has been no systematic research into the role of auditory information for cycling safety.

Cycling safety is a major traffic safety concern in many European countries and in the USA. Cyclists are benefitting less from safety improvements that are reducing the overall number of traffic fatalities (NHTSA, 2012; Steriu,

2012). Although cyclist fatality risk (number of cyclist deaths per distance travelled) may have decreased between 2001 and 2009 in the countries collecting data on the number of kilometres cycled, the decrease is either very slight (Norway), stagnated (the Netherlands) or the risk is still relatively high (Great Britain) (OECD/ITF, 2013; Steriu, 2012). Only in Denmark the fatality risk of cyclists decreased significantly to a very low level. However, in the Netherlands the risk of serious injury among cyclists actually increased over the same period. Cycling is strongly encouraged by governmental policies of many countries (OECD/ITF, 2013) and it is expected to become a central part of the mobility solution in many cities. It is therefore important to identify and address factors that negatively influence cycling safety. Limiting auditory cues from traffic environment may form such a risk.

This paper provides a review of current knowledge regarding the use of electronic devices and the acoustic characteristics of (hybrid) electric cars in relation to cycling safety. This is for the first time that these two aspects are brought together to discuss the potential problem of limiting auditory cues. The objectives of the paper are: (1) to estimate, using literature and crash databases, the extent to which limitations on availability of auditory information while cycling constitutes a road safety hazard and (2) to identify the most important knowledge gaps that need to be addressed for a better understanding of the relation between this potential problem and cycling safety. For that purpose, a proposed conceptual model of the role of auditory information in cycling is used. The paper introduces the conceptual model, describes the methods of literature search and selection and crash data analysis, followed by the results. The most important knowledge gaps and recommendations for future research are presented, and finally the main results and their implications are discussed.

2.2. Conceptual model

Figure 2.1 presents a proposed conceptual model of the role of auditory information in cycling. This integrated model combines the information processing models (Endsley, 1995; Shinar, 2007; Wickens et al., 2004), general driver behaviour models (Fuller, 2005; Hurts, Angell & Perez, 2011) and insights from research in applied auditory cognition (Baldwin, 2012).

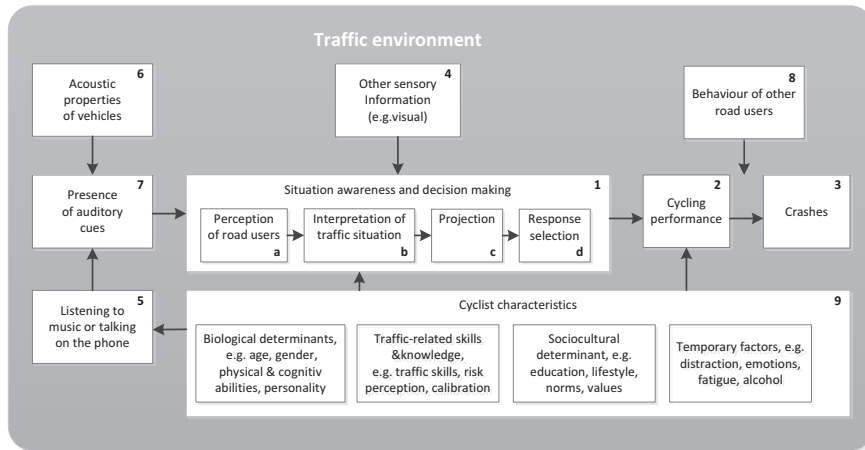


Figure 2.1. Conceptual model illustrating the role of auditory information in cycling safety.

Human beings not only react to physical characteristics of a sound — its pitch, loudness, timbre or duration — by hearing (a sensory process), but a sound is also interpreted (a perceptual-cognitive process) (Baldwin, 2012). Sound perception involves, for example, sound recognition, its identification and location in space. For a cyclist the perception of traffic sound (*box 1a* in *Figure 2.1*) may involve detection, identification of the sound source (as a car, motorcyclist, etc.) and its localisation (e.g. its location, speed), even if it cannot be seen. While acknowledging the relevance of visual – auditory interactions (see, e.g. King, 2009) (*box 4*), the model was specifically designed to address situations in which no visual information is available for cyclists due to visibility obstruction, visual distraction or cyclists’ reliance on auditory information. Indeed being able to hear traffic sounds is considered to be especially important for gathering information about approaching traffic from areas outside one’s field of view (Ashmead et al., 2012; Mori & Mizohata, 1995).

Auditory information can help cyclists to interpret a traffic situation (*box 1b*) and to project future actions (*box 1c*). Those elements, namely perception (*box 1a*), interpretation (*box 1b*) and projection (*box 1c*), form three levels of cyclist situation awareness (Endsley, 1995) — their awareness of the meaning of dynamic changes in the environment. Cyclist situation awareness forms the basis for response selection (*box 1d*) and cycling performance (*box 2*), which in turn has consequences for road safety (*box 3*).

The role of auditory information in maintaining one's situation awareness can be reduced by the use of electronic media devices (such as mobile phones or portable music players) while cycling (*box 5*) and also by a low sound emission of vehicles (e.g. electric cars) (*box 6*). Talking on the phone and listening to music may cause auditory distraction by diverting attention away from the traffic task. Traffic sounds may also simply get masked by speech, music or ambient noise. Auditory cues used by a cyclist to detect and localise other road users can then be reduced (*box 7*), affecting cyclists' situation awareness (*box 1*), cycling performance (*box 2*) and road safety in the end. Crashes (*box 3*) can occur if, in the presence of traffic-related hazards, a degraded cycling performance is not compensated by the cyclist himself or other road users involved.

The bottom of the figure shows the importance of cyclist characteristics (*box 9*) influencing this relationship. Cyclist characteristics refer not only to personal characteristics such as age, experience as a cyclist, skills, knowledge, and physical and cognitive abilities but also to temporary conditions such as fatigue or emotional state. Many other factors in the traffic environment can be expected to influence the strength of the relationships shown in *Figure 2.1*, such as bicycle condition, road infrastructure, weather and traffic-related conditions. Given the scope of this paper, we will not systematically address cyclist characteristics and other possible factors.

2.3. The use of devices and electric cars: combined effects

Encountering a quiet electric car may be more dangerous for cyclists who listen to music or phone than for those who “just” cycle. As the sound intensity decreases with increasing distance to the source (Myers, 2006), quiet electric vehicles are likely to be detected later than the more noisy conventional cars. The use of devices is likely to deteriorate the detection of quiet cars even further due to masking effects. Quieter sounds are generally masked by louder sounds. The higher the sound intensity of the masking sound (e.g. music), the higher the intensity level of the masked sound (e.g. car sound) must be before it can be detected (see, e.g. White & White, 2014). Loud music is therefore more likely to mask quiet electric cars. However, the frequency of the masking and the masked sound is also of great importance. Masking is more likely to occur when music contains similar frequency ranges as the car sound (White & White, 2014). In situations where the visual information is not available (due to visibility obstruction or cyclists' reliance on auditory information when making decisions e.g. to turn), approaching cars — particularly quiet electric

cars — may be detected far too late by a cyclist who is listening to music or conversing on the phone to provide enough time for the proper reaction.

2.4. Methods

This section presents the methodology adopted for the literature review and the crash data analysis.

2.4.1. Literature review

Relevant literature published up to April 2014 was searched for using scientific databases (Scopus, Web of Science, SafetyLit and the library catalogue at SWOV Institute for Road Safety Research). Since only few studies with cyclists were found, the literature concerning pedestrians was searched for. Although the conceptual model focuses on cyclists, we can assume that it applies to a great extent to pedestrians as they also use auditory cues in traffic. The results among pedestrian should be treated with caution, as obviously there are important differences between cyclists and pedestrians. Cyclists, who typically move around faster than pedestrians, have to deal with aerodynamic noise caused by the head displacement through the air (Defrance, Palacino & Baulac, 2010). Furthermore, cyclists sometimes share the road with cars and they often deal with other traffic situations than pedestrians do.

Search terms “cycling”, “cyclist(s)”, “cycling safety” or “pedestrian(s)”, “pedestrian safety” were included in all searches and combined with “music”, “mobile/cell phone(s)”, “distraction” or “media devices”. Keywords: “electric vehicle(s)/car(s)”, “auditory perception” or “traffic sound(s)” were additionally combined with “traffic/road safety”. Studies were excluded if they addressed (1) domains other than road safety (e.g. noise annoyance), (2) sounds other than car sounds (e.g. alerts), (3) the effects of combined use of electronic devices (e.g. listening to music and texting) and (4) exclusively added-on sounds of electric vehicles. Furthermore, studies with small non-representative sample sizes were excluded. This resulted in a list of 28 relevant publications. Additionally, the references of relevant publications were analysed, applying the “snowball” method. In total, 33 studies were included (see *Appendix 1*).

2.4.2. Crash data

As almost all relevant studies with cyclists concerned the Dutch situation (see *Appendix 1*), we focused on crashes in the Netherlands. For this purpose, the

National (Dutch) Road Crash Register (BRON) was used. BRON is based on all crashes reported and registered by the police. It contains a large number of characteristics of the crash and the drivers and casualties involved. Due to a gradual decline of the registration rate of crashes in BRON, especially from 2009 on, supplemental data from Statistics Netherlands and LMR (the National Medical Registration) were used to account for the missing crashes. Those sources contain data from medical practitioners, hospitals and the district public prosecutor 's offices. The crash data involving cyclists were used to:

1. investigate whether, and to what extent, the use of electronic devices was a factor contributing to crashes, and whether and to what extent those crashes were caused by the lack of auditory cues;
2. compare (hybrid) electric cars with conventional cars as far as the crashes involving cyclists and pedestrians are concerned, and assess whether and to what extent the quietness of the (hybrid) electric car has contributed to the crash.

2.5. Results

The first two results sections, The use of devices and crash risk and Electric cars and crash risk, present findings on crash risk from both the literature review and the crash data analysis. The remaining sections describe the results based on the literature review only. *Appendix 1* provides the details of the studies used. We present the research findings in relation to the specific components of the conceptual model (*Figure 2.1*). The numbers of corresponding boxes are given in brackets. As the studies and crash databases rarely dealt with the direct relationships between components as indicated by the arrows in the model, the indirect relationships are presented as well (see also *Figure 2.2*).

2.5.1. The effects of using devices on cycling performance

Table 2.1a shows that listening to music and conversing on the phone (*box 5*, *Figure 2.1*) while cycling does not influence the different aspects describing cycling behaviour (*box 2*) equally. Some aspects of cycling performance are similarly affected by both activities. Findings from observational research show that the number of unsafe behaviours (*box 2*) increased and auditory perception deteriorated (*box 1a*) when cyclists were listening to music or talking on the phone.

A field experiment by De Waard, Edlinger, and Brookhuis (2011) shows that only five to about 20% of cyclists using devices heard all bicycle bell sounds as compared with about 70% of cyclists who were not using devices (*box 1a*). The same study indicates that the type of music and the manner of listening are of importance. Moderate volume or moderate tempo music (through normal earphones) compromised cyclists' auditory perception of the bicycle bells. High tempo music, loud music and in particular music listened through in-earphones impaired even hearing of loud sounds, that is, horn honking. However, cyclists' auditory perception was not affected when they listened to music using one earphone.

Furthermore, in field experiments cyclists rated both listening to music and talking on the phone as more risky than "just" cycling (*box 1b*). Some aspects of cycling performance (*box 2*) (i.e. the number of traffic conflicts found by observations of cycling behaviour on the road, the position on the road and swerving analysed in field experiments) were not affected by either conversing on the phone or listening to music. Other aspects were influenced by one activity only. Two field experiments show that cycle speed (especially when performing a difficult phone task) and response time (*box 2*) were influenced by phoning (De Waard et al., 2010). By reducing speed, cyclists apparently compensate for the high secondary task demand. Cyclists listening to music, however, were observed to disobey traffic rules (*box 2*) more frequently than those conversing on the phone.

A field experiment by De Waard et al. (2010) shows that visual detection (i.e. a number of noticed objects) (*box 4*) was not influenced by listening to music. Field experiments investigating visual detection among cyclists on the phone show mixed results. De Waard, Lewis-Evans, Jelijs, Tucha, and Brookhuis (2014) and De Waard et al. (2010) found that a phone conversation — especially a difficult one — negatively affected the number of noticed objects. However, De Waard et al. (2011), using the same difficult conversation task, found no effect. Surprisingly, the effects of having a handheld versus hands-free conversation on cycling performance did not differ much. In the hands-free condition, response time was shorter, probably due to cyclists being able to operate both hand brakes.

2.5.2. Effects of device use on cycling versus pedestrian performance

Comparing *Table 2.1a* and *b*, we can conclude that the effects of listening to music and talking on the phone among cyclists are generally similar to those

found among pedestrians — suggesting that similar mechanisms may play a role in performance degradation caused by device use.

An interesting aspect investigated by studies with pedestrians is looking behaviour (*box 2*). Research findings are mixed on this aspect. Some observational studies and experiments in virtual environments found no decrease in cautionary looking behaviour (i.e. head turns before crossing the street) while listening to music (Neider et al., 2011; Neider et al., 2010; Walker et al., 2012) or talking on the phone (Neider et al., 2011; Neider et al., 2010; Thompson et al., 2013). However, an observation study by Hatfield and Murphy (2007) and an experiment in virtual environment by Schwebel et al. (Schwebel et al., 2012) found a negative effect of using devices on looking behaviour (Hatfield & Murphy, 2007; Schwebel et al., 2012).

Hatfield and Murphy, who observed decreased cautionary looking behaviour only among females, suggested that females may become more involved in their phone conversations than males, with the result that there is less attention for scanning the traffic situation. An observation study by Walker et al. (2012) also found some gender differences: males listening to music displayed more looking behaviour than those not listening to music, while females showed no differences between the two conditions. This does not have to mean that women who are listening to music are less cautious than men — women may be listening to music at a lower volume than men and may therefore need less compensation.

There is no clarity regarding the effects of device use on the number of conflicts. Field experiments, and some experiments in virtual environments, showed an increase in the number of conflicts among pedestrians who listen to music or talk on the phone (Nasar, Hecht & Wener, 2008; Schwebel et al., 2012; Stavrinos, Byington & Schwebel, 2011). Observations and other studies in virtual environments found, however, no effects (Hyman et al., 2010; Neider et al., 2010).

Table 2.1. a) Summary of the effects of listening to music and phoning on cyclists;
b) summary of the effects of listening to music and phoning on pedestrians.

Effect	Music		Phoning	
	Effect ¹	Study type ²	Effect ¹	Study type ²
<i>(a)</i>				
Missed a bicycle bell	↑ ^a	field	↑ ^a	field
Missed a horn honking	↑ ^a	field	— ^a	field
Speed	— ^{a,b}	field	↓ ^{a,b,c}	field
Response/reaction time	— ^a	field	↑ ^a	field
Lateral position <i>(average position and variation of position)</i>	— ^b	field	— ^{b,c}	field
Detected visual objects	— ^b	field	— ^a ↓ ^{b,c}	field
Risk rating	↑ ^{a,b}	field	↑ ^{b,c}	field
Conflicts <i>(situations where either the observed road user or another traffic participant had to change speed or course to avoid a crash; or near-crash)</i>	— ^b	obs	— ^b	obs
Disobedience of traffic rules	↑ ^b	obs	— ^b	obs
Unsafe behaviours <i>(riding in the wrong direction in the bicycle lane, failing to slow down and look for crossing traffic, riding through the pedestrian crosswalk, riding too slow when entering the intersection, causing crossing traffic to brake to allow the cyclist to cross)</i>	↑ ^c	obs	↑ ^c	obs
Crash risk (self-reported) <i>(music & phoning)</i>				↑ ^{d,f} survey

Continued

Notes: Table 2.1a. ¹ ↑ = increase; ↓ = decrease; — = no effect. ² obs = observation (on the road without the intervention by the researcher), field = field experiment (intervention in the real world).

^a De Waard, Edlinger & Brookhuis (2011)

^b De Waard et al. (2010)

^c De Waard et al. (2014)

^d Goldenbeld, Houtenbos & Ehlers (2010)

^e Terzano (2013).

^f Ichikawa & Nakahara (2008)

Table 2.1. Continued

	Music		Phoning	
	Effect ¹	Study type ²	Effect ¹	Study type ²
<i>(b)</i>				
Speed	— ^b ↑ ⁱ	obs	↓ ^{b,h,i,j}	obs, sim
Response/reaction time	— ^d	sim	↑ ^d	sim
Lateral position (average position and variation of position)	— ^b	obs	↑ ^b	obs
Detected visual objects	— ^{b,c,d}	obs,sim, field	↓ ^{b,c,d}	obs,sim, field
Conflicts (situations where either the observed road user or another traffic participant had to change speed or course to avoid a crash; or near-crash)	↑ ^e — ^{b,j}	sim obs, sim	↑ ^{e,g} — ^{b,j}	obs, sim obs, sim
Unsafe behaviours (not waiting for traffic to stop)			↑ ^h	ob
Mistakes (missed opportunities to cross the street/stopping when there is no car present)	— ^{e,j}	field, sim	↑ ^{e,g,j}	field, sim
Looking at relevant objects	— ^{f,p} ↓ ^{e,i} ↑ ^a	obs, sim sim, obs obs	— ^{a,i,j,g} ↓ ^{e,g,h}	obs, sim sim, obs
Injury rate (number of pedestrian injuries due to mobile phone relative to total pedestrian injuries)			↑ ^f	crash

Notes: Table 2.1b. ¹ ↑ = increase; ↓ = decrease; — = no effect. ² obs = observation, sim = experiment in virtual environment, field = field experiment, crash = crash study.

^a Walker et al. (2012)

^b Hyman et al. (2010)

^c Nasar et al. (2008)

^d Neider et al. (2010)

^e Schwebel et al. (2012)

^f Nasar & Troyer (2013)

^g Stavrinos, Byington & Schwebel (2011)

^h Hatfield & Murphy (2007)

ⁱ Thompson et al. (2013)

^j Neider et al. (2011)

Irrespective of the contradictory results, there are few differences between the effects found among cyclists and pedestrians. However, one difference concerns lateral position: unlike cyclists, pedestrians' lateral position was affected by phoning. The differences between findings do not seem to be related to the use of various research methods, as specific methods cannot be associated with specific results, that is, similar results were obtained with different methodologies, and some studies using similar methodologies obtain contradictory results.

2.5.3. The use of devices and crash risk

The Dutch official crash databases do not record the use of devices as a contributory factor in bicycle crashes (*box 3*). Similarly, no information about the use of electronic devices in crash registration was found in the international literature on cycling safety. Two Dutch surveys among cyclists suggest that the use of devices may have contributed to 7 – 9% of self-reported injury crashes nationally (De Waard et al., 2010; Goldenbeld, Houtenbos & Ehlers, 2010). Also a Japanese survey among students indicates a possible risk-increasing effect from using mobile phones while cycling (Ichikawa & Nakahara, 2008). In this study, the use of a mobile phone while cycling in the past month was related to the experience of a crash or near crash.

Goldenbeld Houtenbos & Ehlers provide a more accurate indicator for the impact of the use of devices on cycling safety levels (2010). While taking into account potentially relevant exposure factors (such as the extent to which cyclists were exposed to hazardous traffic situations), the risk of a self-reported crash for cyclists who used electronic devices on every trip, turned out to be a factor 1.6 higher for teenagers and 1.8 higher for young adults compared with their respective age counterparts who never used devices while cycling. However, for middle-aged and older adult cyclists, no increase in crash risk was found. Both studies (Goldenbeld, Houtenbos & Ehlers, 2010; Ichikawa & Nakahara, 2008) found that the higher the subjective risk ratings of cyclists were, the less often they were involved in a self-reported crash. Those higher ratings of perceived risk found among cyclists who use devices might therefore mean that cyclists are aware of the high secondary task demand and behave more cautiously in traffic.

The only crash study we found involving pedestrians and the use of devices used data on injuries in a representative sample of hospital emergency rooms across the USA (*box 3*). Results showed that an increase in mobile phone subscriptions in the period 2004 – 10 was associated with an increase (from

0.6% to 3.7%) in the share of mobile phone-related injuries among pedestrians relative to all pedestrian injuries. About 70% of the reported injuries related to talking and 9.1% to texting. As texting is considered more distracting than talking, these percentages probably reflect a lower amount of texting than talking while walking.

2.5.4. Hybrid electric cars: detectability and localisation

Studies into the safety consequences of (hybrid) electric cars for vulnerable road users have focused particularly on acoustic characteristics of those cars (*box 6*) and their detectability and localisation (*box 1a*) (see also *Appendix 1*). In those studies hybrid cars (operated in the electric mode⁶) were compared to conventional (Internal Combustion Engine — ICE) cars for various speeds and various ambient noise levels. Only one study (Hong, Cho & Ko, 2013) included a fully electric car — a low speed and light model. Kim et al. (2012a) and Wiener et al. (2006) used conventional and hybrid cars of the same make and model. Other studies do not provide details about the cars used. Comparisons are more conclusive within studies than between them as both the car makes and models used and measurement conditions varied between studies. *Table 2.2* shows that hybrid electric cars were found quieter than conventional ones when stopped or at low speed (*box 1a*). The lower the speed of the cars, the bigger is the difference in the emitted sound level between the two car types. For cars passing by at 10 km/h, the difference ranged from 2 to 8 dB-A. At speeds 15 – 30 km/h hybrid electric cars were found 2 – 3 dB-A quieter than conventional cars. At speeds above 30 km/h, and in some studies already above 15 – 20 km/h, the sound level of two car types do not differ, most likely because of the tyre noise being dominant and not the engine noise.

When driven at low speeds and in relatively quiet backgrounds, (hybrid) electric cars were more likely to remain undetected longer than conventional cars by both sighted and visually impaired pedestrians (see *Table 2.3*). The study of Hong, Cho & Ko (2013) found a difference between an electric and a hybrid car: the former was detected later when stationary or when driven at 30 km/h. Surprisingly, at 20 km/h, the hybrid car was detected later than the electric car. When in stationary, both car types were detected at very short distances. Furthermore, 80% of the participants passing in front of the hybrid

⁶ Mendonça et al. (2013) does not provide information on whether the hybrid car operated in electric mode. Wall Emerson et al. (2011b) cannot ensure that the used hybrid electric car was actually driven in electric mode when going at certain speeds.

car and 97% of those passing in front of the electric car could not perceive the stationary vehicle sound.

Table 2.2. Sound level differences between (hybrid) electric (HE) cars and conventional (ICE) cars by speed and ambient sound levels.

Speed	Ambient sound in dB-A	Comparison of sound levels of HE and ICE cars	Difference in sound levels in dB-A between ICE & HE cars
<i>In stationary</i>			
0 km/h ¹	25	H<ICE	20
<i>Forward constant speed</i>			
7–8 km/h ¹	25	H<ICE	7–8
10 km/h ¹	25	H<ICE	6–7
10 km/h ²	Very low	H<ICE	2–8
15 km/h ¹	25	H<ICE	3–4
15 km/h ⁵	Unknown	H<ICE	0.2
15–30 km/h ⁴	50.6–54.7	H<ICE	2–5
20 km/h ¹	25	H=ICE	0
30 km/h ¹	25	H=ICE	0
32 km/h ²	Very low	H=ICE	0
48 km/h ²	Very low	H=ICE	0
50 km/h ³	43.7–49	H<ICE	2.3
64 km/h ²	Very low	H=ICE	0
<i>Reverse constant speed</i>			
8 km/h ²	Very low	H<ICE	7–10
10 km/h ⁵	Unknown	H<ICE	4
<i>Accelerating</i>			
to 30 km/h ³	43.7–49	H<ICE	8
<i>Slowing down</i>			
From 32 to 16 km/h ²	Very low	H<ICE	0.7

¹ JASIC (2009)

² Garay-Vega et al. (2010).

³ Wiener et al. (2006).

⁴ Wall Emerson et al. (2011b)

⁵ Kim et al. (2012a)

Table 2.3 shows also that hybrid electric cars at low speeds and in higher ambient noise levels were often detected too late to afford safe crossing. Time-to-vehicle-arrival, which is the time from first detection of a target car to the

instant the car passes the pedestrian location, was often less than general time needed to cross the street (about 6 – 7 s). In some situations, a hybrid electric car was detected when only an average of 2 – 3 s away. However, even conventional cars were not always detected at distances allowing safe crossing. Once the ambient sound level was above 45 – 50 dB-A or when curves, hills and road-side trees obscured sounds, conventional cars were often detected too late to cross safely (*box 1a*) (Kim et al., 2012a; Wall Emerson et al., 2011b; Wall Emerson & Sauerburger, 2008).

Vehicle detection is also significantly affected by vehicle speed, listener's age and pavement type. Faster travelling cars generate more noise (Garay-Vega et al., 2010) and as speed increased, cars were detected sooner and thus at greater distance (and sooner) (Barton et al., 2013; Barton, Ulrich & Lew, 2012). The worst detectability levels were found among juveniles and older participants (Hong, Cho & Ko, 2013; Mendonça et al., 2013) and on low-noise pavements, that is, asphalt as opposed to cobble stones (Mendonça et al., 2013). Not only detection of cars but also their correct localisation is important for pedestrians when making crossing decisions. Earlier detection of a car does not, however, guarantee that it is more accurately localised in space. To illustrate, although conventional cars were detected earlier than hybrid cars, judgements about whether the car goes straight or turns right were equally accurate but quite delayed for both car types (Kim et al., 2012b).

Finally, auditory localisation of approaching cars, compared to their detection, is to a higher degree influenced by the signal-to-noise ratio: ambient sound level in relation to the car sound output. A laboratory study of Ashmead et al. (2012) found that at higher levels of ambient sound (60 dB-A or more), acoustic output of individual cars are often too low for pedestrians to be able to distinguish between straight and right-turn paths. In the same study, the signal-to-noise ratio needed to distinguish between these paths was higher than the signal-to-noise ratio needed for vehicle detection.

No studies into the detectability and localisation of (hybrid) electric cars performed with cyclists were found in the literature. Since hybrid cars emit less sound at low speeds, it can be expected that similar differences in detection as for pedestrians will apply for cyclists. However, auditory detection of cars is probably more difficult for cyclists since cyclists, who typically move around faster, have also to deal with aerodynamic noise.

Table 2.3. Detection of (hybrid) electric (HE) and conventional (ICE) cars in relation to time-to-vehicle-arrival and pedestrian crossing time.

Speed in km/h	Ambient sound in dB-A	Car type earlier detected	Time-to-vehicle-arrival in sec. ¹ in brackets: crossing time	Study type ²
<i>In stationary</i>				
0 ^{e7}	40	ICE*		Field
<i>Forward constant speed</i>				
6.5 ^a	45.2	ICE		Lab
6.5 ^a	52.6	ICE		Lab
6.5 ^a	61.7	ICE = HE		Lab
10 ^b	31.2	ICE	C = 6.2; HE = 4.8	Lab
10 ^a	45.2	ICE		Lab
10 ^b	49.8	ICE	C = 5.5; HE = 3.3	Lab
10 ^a	52.6	ICE		Lab
10 ^a	61.7	ICE = HE		Lab
15 ^a	45.2	ICE		Lab
15 ^c	48.7 – 55.1	ICE	C = 8.6; HE = 6.5 (6.9)	Lab
15 ^a	52.6	ICE = HE		Lab
15 ^a	61.7	ICE = HE		Lab
20 ^a	45.2	ICE ≈ HE		Lab
20 ^a	52.6	ICE ≈ HE		Lab
20 ^a	61.7	ICE ≈ HE		Lab
20 ^c	45	ICE		Field
<32 ^{d8}	52.8	ICE, HE**	C = 5.5; HE = 2.1-6.7 (6)	Field
30 ^e	45	ICE*		Field
30, 40 & 50 ^f	62–82	ICE***		Lab
<i>Accelerating</i>				
From stop ^g	unknown	ICE		Field
<i>Slowing down</i>				
32 to 16 ^b	49.8	HE	C = 1.1; HE = 2.3	Lab
32 to 16 ^b	31.2	HE	C = 1.3; HE = 2.5	Lab
<i>Backing</i>				
10 ^b	31.2	ICE	C = 5.2; HE = 3.7	Lab
10 ^c	48.7 – 55.1	ICE	C = 10.1; HE = 9.4 (6.9)	Lab
10 ^b	49.8	ICE	C = 3.5; HE = 2	Lab

¹ Mean; median in italics.

² lab = laboratory study, field = field experiment.

*ICE cars were detected earlier than a hybrid car; the hybrid car earlier than an electric car; **out of three makes of electric cars, two were detected later and one earlier than an ICE car; ***a hybrid car was detected later only when compared with a pickup truck, but not when compared with a small passenger car.

^a JASIC (2009)

^b Garay-Vega et al. (2010)

^c Kim et al. (2012a)

^d Wall Emerson et al. (2011b)

^e Hong, Cho & Ko (2013)

^f Mendonça et al.(2013)

^g Kim et al. (2012b)

⁷ Erratum: The original version of the article contained an incorrect reference.

⁸ Erratum: In the original version of the article, the speed was incorrect.

2.5.5. Electric cars and crash risk

It is difficult to determine whether the relative quietness of (hybrid) electric vehicles contributes to a higher risk of crashes involving pedestrians or bicyclists (*box 3*). Due to the limited operating range of the majority of fully electric vehicles (100 – 170 km), electric cars can be assumed to cover lower average annual kilo- metres and to be driven especially in urban areas. Therefore the share of kilometres driven at lower speeds, where their detectability is lower, is likely to be higher for electric cars than for conventional cars. If the lack of sound from the car were a contributory factor to crashes, the differences between conventional and electric cars should be expected to manifest themselves at low speeds.

Some studies show higher incidence of crashes involving (hybrid) electric cars and vulnerable road users (Hanna, 2009; Morgan et al., 2011; Wu, Austin & Chen, 2011). Research in the USA shows that, in the period 2000 – 08, hybrid cars had a higher incidence rate⁹ of pedestrian and cyclist crashes (35% and 57%, respectively) (Wu, Austin & Chen, 2011). In situations where cars drive slowly (slowing down, stopping, backing up, and parking manoeuvres) the incidence rate of (hybrid) electric cars involved in pedestrian crashes was twice as high as that of conventional cars. Additionally, the number of bicyclist crashes involving (hybrid) electric cars at intersections or interchanges was significantly higher when compared to conventional vehicles.

Similarly, in the UK Morgan et al. (2011) found that proportionately more (hybrid) electric cars hit pedestrians than conventional cars. It is, however, not possible to conclude that (hybrid) electric cars are more dangerous in terms of crash risk than conventional ones as the absolute numbers of reported crashes involving (hybrid) cars were very small in both studies. Furthermore, the crash rates were not corrected for exposure, that is, kilometres travelled by each type of car. With higher exposure there is higher chance of crashes. Without exposure data, the available studies addressing the crash involvement of (hybrid) electric cars, do not provide evidence that (hybrid) electric cars pose a higher safety hazard for pedestrians and cyclists than conventional cars (see Verheijen & Jabben, 2010).

⁹ Incidence rates = the number of vehicles of a given type involved in crashes divided by the total number of that type of vehicle that were in any crashes.

Table 2.4. (Hybrid) electric cars versus conventional cars in pedestrian and bicyclist crashes in the period 2007 – 2012 in the Netherlands by speed limit at the crash location.

Type of passenger car	Crash opponent	Speed limit of the road (km/h)				Unknown
		15	30	50	<50	
Conventional	Pedestrian	47	895	3155	362	239
	Cyclist	86	4497	20761	2376	966
	Total (N = 33.384)	133	5392	23916	2738	1205
	%	0%	16%	72%	8%	4%
(Hybrid) electric	Pedestrian	1	1	13	4	1
	Cyclist	0	16	56	5	3
	Total (N 100)	1	17	69	9	4
	%	1%	17%	69%	9%	4%

Source: DVS (Centre for Transport and Navigation)-BRON.

Quietness of the car as a contributing factor in crashes is not reported in Dutch crash data. *Table 2.4* shows crashes involving a (hybrid) electric car or a conventional car and a cyclist or pedestrian according to the speed limit of the road. Although the number of crashes involving (hybrid) electric cars was low, the distribution of crashes across road types is similar to that of conventional cars. For hybrid cars, it is not known whether or not they were driven in the electric mode at the time of the crash. The majority of crashes involving cyclists and pedestrians occurred in areas with a speed limit of 50 km/h, regardless of car type. In the period 2007 – 12, the percentage of (hybrid) electric cars in the Dutch fleet increased (from 0.15 – to 1.15%) proportionally to crash involvement of these vehicles with a pedestrian or a bicyclist (see *Appendix 2*). However, similar to Hanna (2009) and Morgan et al. (2011), the lack of exposure data and the small number of crashes in which (hybrid) electric cars are involved, makes it impossible to compare the crash risk of (hybrid) electric cars and conventional cars.

2.5.6. Experiences of drivers of (hybrid) electric cars

Two studies investigating the driver perspective (*box 8*) were found: a Dutch survey with drivers of hybrid and electric vehicles (Hoogeveen, 2010) and a field experiment (MINI E) performed in Germany and in France with test drivers driving an electric car (Cocron et al., 2011; Cocron & Krems, 2013; Labeye et al., 2011). The studies suggest that pedestrians and cyclists have problems hearing (hybrid) electric cars when those cars are driven at low speeds. None of the drivers participating in the studies reported a crash caused by the low sound emission of electric vehicles, but a substantial percentage of

the drivers in the MINI E study reported noise-related incidents¹⁰ (box 3). The Dutch study revealed vulnerable road users getting startled or surprised (box 3). In the MINI E study, 35% of drivers identified one or more critical incidents (crucial for traffic safety) and 67% reported less critical incidents involving pedestrians and cyclists and related to the quietness of the electric cars. The reported incidents occurred mainly at low speeds (e.g. at traffic lights, in parking areas or in underground garages) and sometimes while accelerating or in quiet side streets. Similarly, vulnerable road users in the Dutch study got startled predominantly by the vehicles driven up to 25 km/h. Forty-six per cent of the drivers reported observing such reactions among vulnerable road users.

The results also show that a substantial percentage of drivers (31% in the Dutch study and 62% in the MINI E study) do not compensate for the lower sound level of their cars by changing their driving behaviour. Furthermore, the MINI E study shows that as drivers gain experience with an electric vehicle, concerns for pedestrians and cyclists related to low sound emission decrease, most likely because drivers did not encounter as many critical noise-related situations as they might have anticipated. Those who changed their behaviour reported paying more attention (Cocron et al., 2011; Hoogeveen, 2010), actively anticipating and preventing potential hazards, seeking eye contact with pedestrians or even talking to them (Cocron et al., 2011). The lack of behavioural change can indicate that the drivers of electric cars are already relatively careful drivers. Another possible explanation is that they see no reason to adapt their behaviour, for example, because they did not consider driving an electric vehicle to be more dangerous than a conventional vehicle.

2.6. Knowledge gaps and recommendations for future research

In line with the second aim of this paper, this section discusses a selection of research gaps in current research that may need to be addressed for a better understanding of the role of auditory information in cycling safety. To this end, *Figure 2.2* showing which relationships (solid arrows) and which specific aspects have been researched among cyclists and pedestrians is used. Priorities for future research are also provided.

¹⁰ Crashes caused by the low sound emission $\frac{1}{4}$ situations in which a driver reported having been missed by vulnerable road users resulting in a collision; noise-related incidents $\frac{1}{4}$ being missed by a vulnerable road user not resulting in a collision.

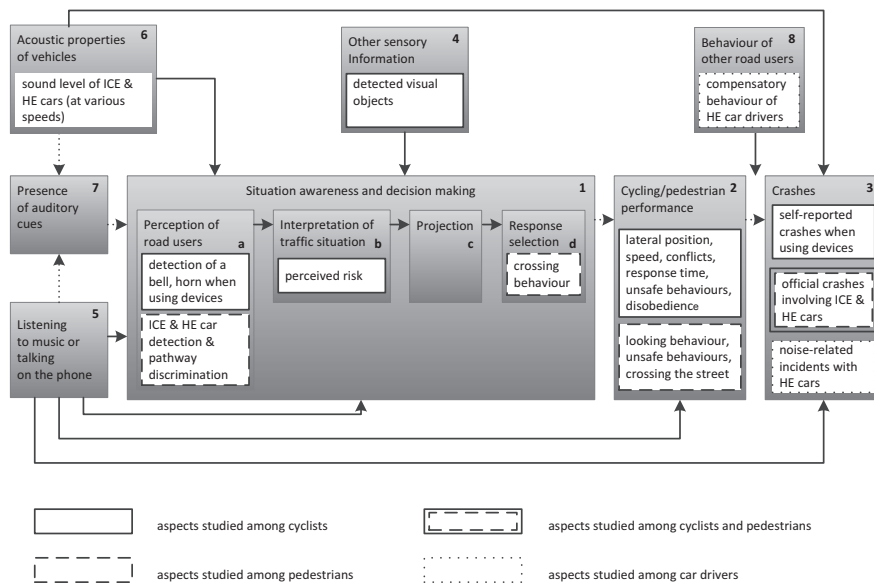


Figure 2.2. Overview of the relationships (solid arrows) examined by the reviewed studies and the specific aspects they dealt with (dashed, dotted and solid boxes).

Relatively little is known about auditory perception (detection and localisation) of traffic sounds (*box 1a*) by cyclists in general and especially when using electronic devices. The traffic sounds used in studies with cyclists were of limited variation (a bicycle bell and a horn). Auditory perception of these sounds may differ from other traffic sounds, e.g. conventional and electric cars. Based on research with pedestrians, electric cars at low speeds can be expected to be detected later than conventional cars. However, due to some important differences between pedestrians and cyclists (see Methods), their use of auditory cues may also differ. Future detection and localisation studies, should therefore be performed with cyclists and include a variety of vehicle sounds. It is also important to explore whether listening to music using one earphone is indeed a safe option for cyclists. This way of listening to music does not seem to impact the detection of auditory stimuli. It can, however, compromise correct localisation of sounds in space for which input from both ears is needed (Grothe, Pecka & McAlpine, 2010) and therefore may yet pose a safety hazard.

It is unknown to what extent the lack of auditory cues from traffic impacts crash risk. There appear to be no objective measures of estimating potential danger (*box 3*) caused by electric cars and the use of electronic devices while cycling. The use of subjective assessments to calculate the crash risk associated with the use of devices while cycling has important disadvantages such as possible non-accurate recall, dishonest reporting, selective non-response bias and does not guarantee a causal relationship. With regard to electric cars, the safety performance of these cars cannot be easily compared to that of conventional cars, primarily due to the lack of exposure data. It is therefore important that future studies collect adequate exposure data necessary to understand crash risk in relation to electric car use and device use while cycling. It is worth mentioning that the reduced sound levels, potentially risky for cyclists today, do not necessarily have to be that risky in the future. A transition from the current fleet to the one containing a substantial share of hybrid and/ or electric cars may cause cyclists to become more aware of their potential presence and behave accordingly. Cyclists may also eventually learn to rely less on auditory information while cycling and listening to music or talking on a mobile phone. They may compensate for the limited auditory input by, for example, increasing visual attention (for other examples of behavioural adaptation in traffic see Rudin-Brown & Jamson, 2013).

The existing crash data in the Netherlands are also not detailed enough to determine whether bicycle crashes involved the use of devices, or whether crashes between electric cars and cyclists were caused by compromised auditory perception. There may be some other aspects related to the use of devices or electric cars which make them potentially dangerous: some characteristics of cyclists who use devices (e.g. sensation seeking), characteristics of traffic environment when cycling and using devices (e.g. dense traffic), specific characteristics of drivers of electric cars (e.g. extra concern for the environment especially in case of the early adopters) or car condition (hybrid electric cars are generally much newer than the mix of conventional cars and newer cars meet higher safety standards, Cooper, Osborn & Meckle, 2010)¹¹. For this paper, the influences of such potentially relevant factors have not been studied systematically. Future studies should focus more in depth on those factors.

¹¹ Safety standards in general, but also standards specific for pedestrian protection, such as the design of softer and more forgiving car fronts (see, e.g. www.euroncap.com/home.aspx).

The impact of a phone conversation on visual attention (*box 4*) is an unresolved issue. Although the model proposed in this paper specifically addresses situations in which no visual information is available, it is very important to explore auditory influences on visual perception of cyclists. If speaking on the phone turns out to impair visual perception (as two out of three studies showed), the possible compensation for the missed auditory information provided by the visual information may not occur. Furthermore, it is unknown how the use of devices and quiet cars impact the essential role of auditory cues in orienting visual attention towards the sound source, especially towards approaching vehicles outside of cyclists' visual field of view. Future studies should explore how the auditory and visual systems work together to facilitate cyclists' detection and localisation of other road users. No research about possible compensatory behaviour of car drivers who encounter a cyclist using electronic devices (*box 8*) could be found. Car drivers may, for example, drive more carefully knowing that more and more cyclists are using various electronic devices and therefore compensate for the possible dangerous behaviour of the cyclist.

Finally, not much is known about the use of electronic devices by cyclists in countries outside the Netherlands. Established cycling cities (such as Amsterdam, Utrecht, Copenhagen) differ in terms of cycling behaviour and bicycling infra-structure from cities where cycling is less popular (Chataway et al., 2014). Cyclists in countries where cycling is popular may also be more used to the presence of other "silent road users" (i.e. other cyclists) and therefore rely less on auditory information when detecting and localising other road users. This limitation of "the state of the art" may limit generalizability of the results concerning cyclists using electronic devices to countries in which cycling is less popular. We recommend therefore studying the effects of limitations on availability of auditory information with cyclists in other countries.

2.7. Main findings and their implications

This paper aimed to review current knowledge on the road safety consequences of using electronic devices while cycling and the effect of lower sound emission of (hybrid) electric vehicles on the behaviour and safety of vulnerable road users. Although for both topics reviewed no objective evidence of increased crash risk was found, there are reasons for concern. Listening to music and speaking on the phone negatively influence auditory perception, cycling performance and self-reported crash risk. With regard to

electric cars, the recurring problem is their quietness at low speeds (generally up to 15 km/h). (Hybrid) electric cars are more difficult for vulnerable road users to detect, especially in environments with moderate and high ambient noise. These results have a number of implications. Those implications are potentially greater in situations where cyclists use solely auditory information, for example, when visibility is obscured or cyclists choose not to use the visual information available.

2.7.1. Car speed

Limitations on availability of auditory information seem to especially impact traffic environments where cars are driven at low speeds. Slower cars (both conventional and electric) generate less noise and are detected later and localised less accurately than faster cars. Slower speeds are generally considered safer for vulnerable road users. As speeds get higher, crashes result in more serious injury (Rosén, Stigson & Sander, 2011) and the likelihood of a crash increases (due to the longer braking distance and due to driver's limited capacity to process information and act on it). However, even at low car speeds, collisions can still have serious consequences for pedestrians and cyclists, especially the elderly and young children. Electric cars at low speeds, due to their low-noise emission and therefore their decreased detectability, seem to pose an even greater risk for vulnerable road users than conventional cars driving at the same low speed.

Not only low car speeds should raise a concern in the discussion on the role of auditory information for cyclists. From the perspective of auditory perception faster moving vehicles seem safer, as both conventional and electric cars at higher speeds indeed offer suitable acoustic cues to other road users. However, cyclist's failure to detect and localise a fast car can increase the likelihood of a fatal injury — speed kills. Listening to music and talking on the phone restrict auditory perception of cyclists and can therefore be expected to lead to detection and localisation failures.

2.7.2. Combined effects: use of devices and electric cars

In the introduction, we have suggested that encountering a quiet (hybrid) electric car may be especially dangerous for cyclists who listen to music or talk on the phone. Research findings presented in this review do not allow hard conclusions, since no studies were found where the use of devices by cyclists was combined with the sound of approaching cars. Based on studies including sounds of a bicycle bell and a horn, we could expect that auditory detection of

various types of cars will at least to some extent be negatively affected by the use of electronic devices. The use of devices may, however, turn out to prevent a car sound from reaching the cyclist irrespective of vehicle type, especially when acoustic input of electric and conventional cars does not differ much from each other — which is especially likely at speeds 20 km/h and above.

2.7.3. Add-on sounds

To improve detectability of (hybrid) electric cars, various developments have been set in motion to provide these vehicles with artificial sound (GRB, 2013; NHTSA, 2013). Some government agencies (e.g. in Japan, the USA, European Parliament) are working on standards for a minimum sound level emitted by vehicles (European Parliament, 2013). Add-on sounds may potentially provide some improvement in detectability of electric cars, but at the cost of increased noise levels, which according to Yamauchi et al. (2010) will be unacceptable in urban situations. Even if these new ambient sound levels are realised, some cars will still be too silent. From the traffic safety perspective, negative effects may appear, for instance in the presence of an artificial sound drivers may think that vulnerable road users can hear them and therefore may not drive as carefully as they would without the added sound (Sandberg, 2012; Sandberg, Goubert & Mioduszewski, 2010).

Other solutions to the problem of low detectability can be suggested, e.g. pedestrian/ cyclist detection systems and the use of cobbled pavements in low-speed traffic environment. Cobblestones reach very high detection percentages for both conventional and hybrid cars driven at speeds above 30 km/h across various ambient sound levels (Mendonça et al., 2013). The suitability of cobblestones for ensuring high detectability of vehicles at lower speeds, however, still needs to be explored.

2.8. Concluding remarks

The concerns regarding the potential negative impact of restricted auditory perception among cyclists (and pedestrians) should be taken seriously. Cycling, in recent years strongly encouraged by governmental policies (see OECD/International Transport Forum, 2013), is expected to become a central part of the mobility solution in many cities. Addressing cycling problem areas is therefore of critical importance. Future studies should cover important

research gaps for a better understanding of the relation between limitations on auditory information while cycling and cycling safety. Especially transition periods, during which cyclists have to cope with a mix of vehicles characterised by various acoustic properties, seem potentially risky for cyclists.

3. Auditory localisation of conventional and electric cars ¹²

The previous chapter identified auditory localisation of traffic sounds by cyclists as an important knowledge gap in current research. This chapter addresses this knowledge gap by investigating auditory localisation of conventional and electric cars in a laboratory setting by participants in three age groups (teenagers, middle-aged and older adults). Two aspects of auditory localisation are of interest: location from which the car sound is coming and whether the car is approaching or receding. Localisation accuracy concerning those two aspects is examined for vehicle motion paths relevant for cycling activity.

Section 3.1 provides background information about human sound localisation and presents the rationale and the hypothesis of the study. *Section 3.2* presents the methods used in the study describing the participants, sound stimuli, apparatus, task, procedure and data analysis. Stimuli in this study were presented in an acoustically treated room and comprised sounds from conventional and electric cars driven at three speeds in two ambient sound levels. The results are reported in *Section 3.3*. *Section 3.4* discusses the results and their implications for cycling safety, e.g. proposals regarding the addition of artificial sound to quiet (electric) vehicles.

¹² This chapter was first published in Transportation Research Part F: Stelling-Kończak, A., Hagenzieker, M., Commandeur, J.J.F., Agterberg, M.J.H. & Van Wee, G.P. (2016). *Auditory localisation of conventional and electric cars: Laboratory results and implications for cycling safety*. Transportation Research Part F: Traffic Psychology and Behaviour, vol. 41, Part B, p. 227-242.

ABSTRACT When driven at low speeds, cars operating in electric mode have been found to be quieter than conventional cars. As a result, the auditory cues which pedestrians and cyclists use to assess the presence, proximity and location oncoming traffic may be reduced, posing a safety hazard. This laboratory study examined auditory localisation of conventional and electric cars including vehicle motion paths relevant for cycling activity. Participants (N = 65) in three age groups (16–18, 30–40 and 65–70 year old) indicated the location and movement direction (approaching versus receding) of cars driven at 15, 30 and 50 km/h in two ambient sound conditions (low and moderate). Results show that low speeds, higher ambient sound level and older age were associated with worse performance on the location and motion direction tasks. In addition, participants were less accurate at determining the location of electric and conventional car sounds emanating from directly behind the participant. Implications for cycling safety and proposals for adding extra artificial noise or warning sounds to quiet (electric) cars are discussed.

3.1. Introduction

Vision and visual attention are important for safe navigation through the traffic environment (e.g. Owsley & McGwin, 2010; Schepers et al., 2013). However, in some instances, the auditory perception of traffic sounds and vehicle movement may be crucial for road users, especially for pedestrians and cyclists. Auditory perception is considered especially important for gathering information about approaching traffic from areas outside one's field of view, or when visibility is obstructed (Ashmead et al., 2012; Barton, Ulrich & Lew, 2012; Mori & Mizohata, 1995).

Two recent trends have generated interest in and concerns about the use of auditory signals by cyclists and pedestrians. One trend is the increasing number of electric and hybrid cars which, when driven at low speeds, are quieter than internal combustion cars (Garay-Vega et al., 2010; JASIC., 2009; Kim et al., 2012a). The number of electric vehicles is expected to increase sharply as many European countries set ambitious sales or stock targets for electric cars in the near future (IEA/EVI, 2013). The other trend concerns the proliferation of portable electronic media devices used to make a phone call or listen to music. Many cyclists and pedestrians use electronic devices when on the road. Observational studies found that about 3–3.5% of cyclists use a cell phone and 8–9% listen to music whilst cycling (De Waard et al., 2010; De Waard, Westerhuis & Lewis-Evans, 2015; Terzano, 2013). In a survey of Goldenbeld et al. (2012), 15% of cyclists reported listening to music and 3% of cyclists reported using their phone on each or almost every trip.

Studies on the auditory perception of traffic sounds have mainly been carried out with pedestrians and focused on the importance of auditory information

for pedestrian safety (e.g. Garay-Vega et al., 2010; Hong, Cho & Ko, 2013; Mendonça et al., 2013; Wall Emerson & Sauerburger, 2008). There has as yet been no systematic research into the role of auditory information in cycling safety.

Cycling safety is a major traffic safety issue both in many European countries and in the USA. Cyclists benefit less from the safety improvements that have contributed to the overall reduction in the number of traffic fatalities (NHTSA, 2012; Steriu, 2012). Although cyclist fatality risk (number of cyclist deaths per distance travelled) decreased between 2001 and 2009 in the countries collecting data on the number of kilometres cycled, only in Denmark was the decrease significant and to a very low level. In other countries, the reduction of fatality risk was either very slight (Norway), there was no reduction (the Netherlands) or the risk remained relatively high (Great Britain) (OECD/ITF, 2013; Reurings et al., 2012; Steriu, 2012). Furthermore, over the same period, the risk of serious injury for cyclists in the Netherlands actually increased (Reurings et al., 2012).

Considering the negative developments in cycling safety, the popularity of electronic devices amongst cyclists and the ambition of many countries to increase the share of electric vehicles, gaining more insight into the role of auditory perception for safe cycling is important.

3.1.1. Auditory detection and localisation of traffic sounds

One of the auditory processes which is essential for efficient human performance and safety, is sound localisation (Baldwin, 2012). The sound of an approaching vehicle, an object falling or a child crying can often be heard before it can be seen. It is not only important to detect the presence of relevant objects or persons, but also to correctly localise them in space. The perception of other road users, involving their detection, identification and localisation, can help cyclists to interpret a traffic situation (see also Wickens' information processing model; 2004) and project future actions. These elements: perception, interpretation and projection form three levels of situation awareness (Endsley, 1995) – awareness of the meaning of dynamic changes in the environment. A cyclist's situation awareness forms the basis for the response selection and cycling performance, which in turn has consequences for road safety (see also the model of Stelling-Kończak, Hagenzieker & Van Wee, 2015).

A person's ability to localise the source of a sound in the horizontal plane depends primarily on the presence of two ears located on either side of the human head. As a result, a sound coming at the cyclist from an angle has a different sound intensity (interaural intensity difference, IID) and arrival time at each ear (interaural time difference ITD) (e.g. Baldwin, 2012). Furthermore, the filtering properties of the human body, including the torso, head, and pinnae help the cyclist to determine whether the sound is coming from the front or from the rear (e.g. Blauert, 1997). The IID is the dominant localisation cue for high frequency sounds, whilst the ITD is the dominant cue for low frequency sounds. Localisation of approaching cars requires the use of both IIDs and ITDs, as car sounds contain both low and high frequencies (e.g. Morgan et al., 2011).

Several studies have examined the accuracy of the auditory localisation of traffic sounds by pedestrians (e.g. Barton et al., 2013; Barton, Ulrich & Lew, 2012; Kim et al., 2012b; Wall Emerson et al., 2011a). Unlike pedestrians, who are mostly segregated from traffic, cyclists often share the road with other vehicles. Cyclists also typically move faster than pedestrians. Cyclists' speed and position in the middle of often faster-moving traffic requires timely manoeuvring and responsibility regarding the safety of other road and path users. These differences between cyclists and pedestrians may imply differences in the use of auditory cues: cyclists may be more frequently exposed to relevant auditory cues from traffic, and they may have more experience in tracking a greater range of vehicle motion paths. The pedestrian population may, therefore, not be comparable to cyclist population (especially in countries where cycling is not very popular). Consequently, the research findings concerning the pedestrian use of auditory cues may not directly apply to cyclists.

Taking into account the results of research with pedestrians and the differences between cyclists and pedestrians mentioned above, a number of unresolved issues concerning the perception of auditory signals important for cyclists navigating the traffic can be identified. First, the localisation accuracy of different car motion paths relevant for cycling activity is unknown. The localisation decisions investigated amongst pedestrians are limited to motion paths crucial for pedestrian crossing decisions, i.e. discriminating between either a car approaching from the left and from the right (Barton et al., 2013; Barton, Ulrich & Lew, 2012; Pfeffer & Barneclutt, 1996) or a car continuing straight and turning right (e.g. Ashmead et al., 2012; Kim et al., 2012b; Wall Emerson et al., 2011a). Research findings show that adult pedestrians are

generally good at the auditory localisation of cars in motion (90% or more of cars were correctly localised, Ashmead et al., 2012; Barton, Ulrich & Lew, 2012; Wall Emerson et al., 2011a), especially when the cars are approaching at higher speeds. About 95% of the cars travelling at 19 km/h or faster were correctly localised and about 84% of the cars driven at 8 km/h (Barton, Ulrich & Lew, 2012). Slower cars generally emit less tyre and engine noise and have a different frequency profile than faster cars (Garay-Vega et al., 2010; JASIC., 2009).

Furthermore, a higher percentage of the cars approaching from the right was correctly localised compared to the cars approaching from the left (Barton, Ulrich & Lew, 2012). In the same study the cars coming from the right were also detected sooner (and thus at greater distance) than those from the left. The authors suggest that this rightward bias may be due to neurological organisation of the auditory cortex. In this study, however, no audiometric measurements were performed. Therefore, it cannot be excluded that the found differences were caused by asymmetric hearing thresholds (different hearing ability in each ear).

As mentioned above, cyclists often engage in multiple manoeuvres in the middle of faster-moving traffic approaching from various directions. It is therefore important to investigate to what extent road users can distinguish between various motion paths. Based on fundamental research into human auditory perception of static broadband noises (Blauert, 1997), we can expect more localisation errors for lateral and rear sound source positions than for frontal positions.

Second, localisation accuracy of age groups particularly vulnerable from the perspective of cycling safety has not been investigated yet. In EU-countries cyclists over 60 years old represent a large proportion of cyclist fatalities (50%; Candappa et al., 2012). There is, furthermore, a peak in cyclist fatalities amongst teenagers aged between 12 and 17, the age of increasing cycling autonomy. Older and teenage cyclists are also of interest from the perspective of the auditory perception of traffic sounds. Young cyclists, compared to other age groups, are more often engaged in activities that can reduce auditory cues from traffic, such as listening to music or talking on the phone (Goldenbeld et al., 2012). The elderly seldom use electronic portable devices whilst cycling. However, decline in hearing acuity with advancing age (e.g. Schieber & Baldwin, 1996) may have implications for the use of auditory cues by older cyclists.

Research shows that the localisation accuracy of vehicles in motion, specifically the left–right discrimination, is lower for younger children (8–9 years old) than for adults (81% versus 96% of correctly discriminated cars) (Barton et al., 2013). It is unknown at what age a youngster’s capability to localise vehicles in motion reaches adult levels. Based on fundamental research, showing that children aged 7–10 can already localise static broadband noises at adult levels (Otte et al., 2013), it can be expected that teenagers approach adult levels of accuracy in the localisation of vehicles. As for the elderly, a study by Mendonça et al. (2013) found that the vehicle detection percentages for adults older than 60 were on average lower than those for adults below 60. Studies investigating the ability of older adults to localise static sounds demonstrate a decline with advancing age (in horizontal locations: Briley and Summerfield, 2014 and Dobрева et al., 2011; in vertical locations: Otte et al., 2013; Briley & Summerfield, 2014; Otte et al., 2013). Therefore, it can be expected that older adults are less accurate at localising moving cars than younger adults.

Third, the extent to which approaching cars can be distinguished from receding ones has hardly been investigated. From the safety point of view, it is especially important that road users correctly identify cars which are approaching. The only study in this field that we found was with children (5, 8 and 11 years old) (Pfeffer & Barnecutt, 1996). The study shows that as children grow older, their accuracy in auditory perception of vehicles in motion increases – on the movement discrimination task (discriminating between approaching, receding and passing cars) eleven year-olds responded correctly almost twice as often as 5-year-olds. However, 11-year-olds were still not very accurate – for both approaching and receding sounds, their accuracy was around 65%. To our knowledge, the accuracy of movement direction of older age groups has not been investigated yet. Fundamental research shows that approaching (looming) sounds, critically important from an evolutionary perspective, are better discriminated than receding sounds and are superior to other types of moving stimuli in attracting attention (Neuhoff, Long & Worthington, 2012; Von Mühlénen & Lleras, 2007). Therefore, it can be expected that auditory localisation of approaching cars is more accurate than that of receding sounds.

Fourth, little is known about how accurate sighted road users are at localising electric cars. A few studies have compared the accuracy of the localisation of conventional and/or hybrid electric cars (with and without added sound) (Ashmead et al., 2012; Kim et al., 2014; Kim et al., 2012a; 2012b; Wall Emerson

et al., 2011a). All but one of these studies (Ashmead et al., 2012) was performed amongst the visually-impaired. A study by Kim et al. (2012b) comparing conventional and hybrid electric cars without add-on sound, showed that although conventional cars were detected earlier than hybrid electric ones, there was no difference regarding the accuracy of localisation (i.e. distinguishing straight from right-turn paths).

Similarly, Wall Emerson et al. (2011a) did not find significant differences in the localisation accuracy of the two car types. However, as a relatively small sample consisting of blind pedestrians was used in this study, the generalizability of the findings may be limited. The visually-impaired, who rely on sounds to navigate the traffic, may differ in their use of auditory cues than sighted road users.

Research performed with sighted participants showed that at the higher levels of background noise (60 dB-A or more), the acoustic properties of individual cars, irrespective of vehicle type, were often too weak for pedestrians to be able to track their motion path (distinguish between straight and right-turn paths) (Ashmead et al., 2012). In the same study, the signal-to-noise ratio (ambient sound in relation to the car sound output) needed to distinguish between straight and right-turn paths was higher than the signal-to-noise ratio needed for vehicle detection. This is in line with fundamental research findings showing that to get the same accuracy levels, higher signal-to-noise ratios are needed for auditory localisation than for detection (Abouchacra et al., 1998; Abouchacra & Letowski, 2001). When driven at speeds below 20 km/h, electric cars are generally quieter than conventional cars and thus have a lower signal-to-noise ratio. Therefore, we can expect electric cars at low speeds to be localised less accurately than slow-moving conventional cars.

3.1.2. The present study

This laboratory study aims to broaden the scope of previous studies by addressing the unresolved issues mentioned above. The current study presents an integrated approach: in addition to a variety of motion paths relevant for cycling activity and the two car types, factors shown to be relevant for the auditory perception of cars were included, that is, car speed, car motion direction (approaching versus receding) and ambient sound level.

A laboratory setting was chosen for several reasons. As many variables were of interest, an experiment in real traffic would not have been practically feasible. Besides, laboratory conditions allowed us to control the car speed, motion paths and ambient sound level. Next, since little is known about the auditory perception of signals important for the cyclist's traffic environment, starting with an experiment in a safe setting is preferable from an ethical perspective. Furthermore, findings from this research may help to narrow the focus of future real-world studies, which is desirable as studies of this type provide limited ability to manipulate variables and are often very time consuming and potentially more risky for participants.

Sound stimuli from four cars were presented separately to participants in three age groups: teenagers, younger adults and the elderly. Speeds typical of Dutch built-up areas, that is 15 km/h: 'woonerfs' (roads in residential district), 30 km/h: urban access roads and 50 km/h: urban distributor roads, were used since these are the locations for the majority of accidents involving cyclists in the Netherlands (Reurings et al., 2012).

The following detailed hypotheses were tested in this study:

1. Conventional cars are localised more accurately than electric cars, especially when driven at 15 km/h.
2. Cars driven at low speeds are localised more accurately than cars driven at higher speeds.
3. Approaching cars are localised more accurately than receding ones.
4. The localisation accuracy of cars in a lateral and rear position is lower than for front position.
5. The localisation accuracy of older adults is lower than that of adolescents or middle-aged adults.
6. Cars driven in a low ambient sound level condition are localised more accurately than cars driven in a moderately noisy ambient condition.

3.2. Methods

3.2.1. Participants

Sixty-five participants in three age groups participated in the study: 16–18 years old ($N = 20$; $M = 16.8$; $SD = .7$; 11 females); 30–40 years old ($N = 21$; $M = 35.9$; $SD = 2.9$; 13 females) and 65–70 year old ($N = 24$; $M = 67.4$; $SD = 1.7$; 10 females). They were recruited through invitation letters sent to persons living in the vicinity of the test location (Radboud University of Nijmegen), through

newspaper advertisements, flyers and via informal contacts. Participants were included if they cycled regularly and reported no major hearing deficiencies. Sixty-three participants cycled at least 1 or 2 days a week, the two remaining participants cycled a few times a month.

Each participant's hearing thresholds were measured using an audiometer. None of the participants was excluded due to hearing loss, as our objective was to reflect hearing capacities of the general population. The clinical measurements of the participants' hearing threshold demonstrated that seventeen older adults had hearing loss (thresholds ≥ 20 dB HL for 0.5, 1, 2 and 4 kHz for both ears). In the age groups 16–18 years and 30–40 years no significant hearing loss was observed, which is in line with normative data for the general population (International Organization for Standardization, 2000). Only one participant in these two groups demonstrated thresholds between 30 and 45 dB HL (for 0.5 and 4 kHz frequency and for both ears). Furthermore, a significant hearing loss was observed in the oldest age group (65–70 years) for the 4 kHz frequency. At this frequency, eight of the older adults (25%) demonstrated a moderate-to-severe hearing loss of (>40 dB HL), which matches normative data for the general population (International Organization for Standardization, 2000). Our data is also in line with other studies showing more pronounced hearing loss at high frequencies than at low frequencies amongst older adults (Burge & Burger, 1999; Oh et al., 2014; Otte et al., 2013).

To examine the association between hearing abilities and localisation accuracy, Pure-Tone Average (PTA, a calculation routinely used to determine hearing impairment; see e.g. Gelfand, 2009) hearing levels across both ears for each participant were obtained by averaging the pure tone thresholds of 0.5, 1, 2 and 4 kHz. Hearing loss, defined as a PTA > 30 dB HL, was present in eleven participants. The association between age group and hearing abilities was significant: $\chi^2(2) = 16.75, p < .001$ (see also *Table 3.1*). All adult participants gave informed consent. For underage participants, the informed consent of their caregivers was additionally obtained. Each participant received a gift voucher of €25.

Table 3.1. Percentage of participants with hearing loss per age.

Age group		Hearing loss
16–18	Count	1
	% within Age group	5%
30–40	Count	0
	% within Age group	0%
65–70	Count	10
	% within Age group	41.7%
Total	Count	11
	% within Age group	16.9%

3.2.2. Stimuli

Recordings of five cars were gathered with a Sonosax SX-62R recorder and a DPA 4017 directional microphone. The microphone was positioned 2 m from the centre of the car's travel path 1.7 m above the ground (average cyclist's eye level). Three conventional cars (Lancia Delta, Toyota Corolla and Opel Astra station), one fully electric (Peugeot Ion) and one hybrid electric car driven in electric mode (Toyota Prius) were recorded. The cars were passing the recorder location from left to right at three speeds representative of urban areas where cars can encounter cyclists: 15 km/h; 30 km/h and 50 km/h. To minimise ambient sound, the recordings were performed in the evening on a quiet residential asphalt road (with speed limit of 50 km/h) with no other road users present on or near the road. Unfortunately the recordings of the Toyota Prius could not be used in the experiment as the car produced some unwanted noise during the recording.

Besides the sounds of the passing cars, a reference sound (69 dB-A) was recorded to calibrate the intensity levels of car sound stimuli in the lab. The recordings were supplemented with background recordings to create scenarios representative of cycling settings. In order to limit the effect of noise level and spectral fluctuations of the background sound on the localisation of approaching and receding cars, the background sound was a continuous traffic noise produced by cars passing simultaneously on a nearby main road.

The sound stimuli were created with Audacity 2.0.2 software by cutting out 5-s segments of the recordings. The approaching car segments stopped 0.5 s before the car reached the microphone – this was to minimise fear or avoidance

amongst participants resulting from an approaching car coming too close. The segments with the receding cars started 0.5 s after the car reached the microphone. In total 24 segments were created (4 cars × 3 speed levels × 2 directions (approaching vs. receding)).

The segments were then converted to 8-channel sound files. One of the seven first channels – depending on which speaker was used to present the sound (see *Section 3.2.3*) – was used for presenting car sounds. Ambient sound was presented with all seven channels either at 44–45 dB-A: low ambient sound condition or at 53 dB-A: moderate ambient sound level condition. The two levels represent respectively a relatively quiet residential area and a moderately noisy suburban area (Garay-Vega et al., 2010; JASIC., 2009; Kim et al., 2012b). The study excluded noisy urban environments as previous studies suggested that it is very difficult to detect the presence of a single car in those environments (Ashmead et al., 2012; Wall Emerson & Sauerburger, 2008).

The sound stimuli had the following characteristics:

- A continuous ambient noise, either at low or moderate level, was presented during the experiment, also during the response time.
- In each trial one second of ambient noise was presented followed by 5 s of either approaching or receding sound.
- All sound files had the same length.

3.2.3. Apparatus and task

The experiment was conducted in an acoustically treated room (absorbing frequencies down to 500 Hz) with a background noise level of 20 dB-A. Auditory stimuli were presented via a Motu MK3 HybridLite audio interface connected to a 13.3 in. HP laptop and seven KRK Systems RP6 studio monitors. The monitors were mounted on a speaker stand 92 cm above the floor and arranged in a circle of 1.2 m radius at intervals of 45° (see *Figure 3.1* and *3.2*). The participants were seated in a chair at the centre of the circular array of 7 loudspeakers.

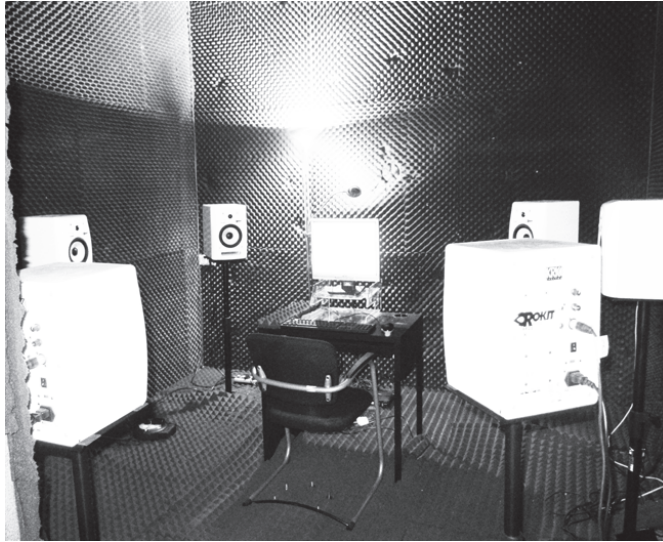


Figure 3.1. Photograph of the lab.

Auditory stimuli were presented in a 2 (car type: conventional versus electric) \times 3 (speed: 15, 30 and 50 km/h) \times 2 (direction: approaching versus receding) \times 7 (location: 7 loudspeakers) design. Three conventional car sounds (of three conventional car models) and one electric car sound (duplicated sound of the electric car to get the same number of trials as with conventional cars) were presented. Participants listened in total to 252 trials.

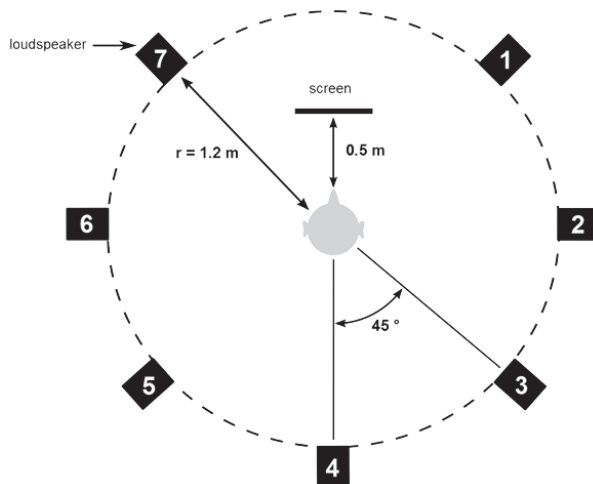


Figure 3.2. Position of the subject and loudspeakers.

In each trial, after the sound of a car was presented, participants were asked to indicate:

1. From which loudspeaker the car sound was coming: Location discrimination.
2. Whether the car was approaching or receding: Movement direction discrimination.

The responses were given by selecting two radio buttons: one corresponding to the position of the loudspeakers in the test room and the other in the middle of the circle (see *Figure 3.3*). Participants had 8 s to answer the two questions. After having selected the answers to both questions, or after 8 s had passed, the programme would automatically proceed to the next trial. Custom software was written to present the sound files in a random order across participants and to record the participant's responses to each trial. During the experiment the participants were free to turn their head.

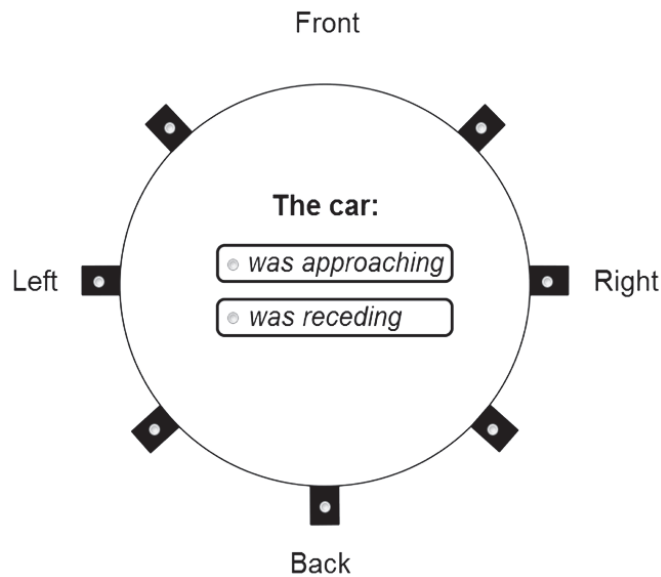


Figure 3.3. Answer options (translated from Dutch) used in the experimental and practice task.

3.2.4. Procedure

First pure-tone audiometric measurements were performed with an Interacoustics clinical audiometer AD229 at 500 Hz, 1, 2 and 4 kHz using (standard 2 down – 1 up procedure) to assess participants' hearing levels. Within each age group participants were randomly assigned to one of the two ambient sound conditions. The participant was then seated in the middle of the speaker array on a chair, the position of which was fixed to ensure that the ears of the participant were between the right and the left speaker (see *Figure 3.2*). After being told to imagine that they were a cyclist riding along a road and being instructed (both verbally and in writing on the laptop screen) about the task, participants performed a practice session consisting of 10 trials to familiarise themselves with the task and use of the response buttons, and to give them the opportunity to ask questions. If required, participants were allowed one extra practice session to ensure they understood the protocol. The experimental trials followed in three blocks and took about 60 min to complete: after each 84 trials, participants were allowed to take a short break. At the end of the experiment, participants were asked to fill in a questionnaire including demographic measures (sex, age, education) and questions about their cycling frequency, duration and purpose.

3.2.5. Analysis

All analyses were conducted using the GENLINUX procedure in SPSS Statistical Software (version 21). The experimental design was a mixed design with age group (with three levels), hearing loss (with two levels) and ambient sound condition (with two levels) as between-subjects factors, and car type (with two levels), direction (with two levels), speed (with three levels), and speaker (with seven levels) as within-subject factors. Three sounds of each car type (for conventional cars: sounds of three different conventional cars; for electric cars: the sound of the electric car presented three times), due to the three trials, were presented in each cell of this design.

Since each location response (speaker number) was scored either 1 (correct) or 0 (incorrect loudspeaker or non-response) and each direction response (approaching versus receding) was scored either 1 (correct) or 0 (incorrect or non-response), the two dependent variables in this experiment were the number of correct location responses out of three trials and the number of correct direction responses out of three trials. Both dependent variables could therefore only take on the values 0, 1, 2, or 3 (correct responses out of three trials).

Since the two dependent variables were not continuous but binomial variables, a standard repeated measures analysis of variance could not be applied. Two separate generalized linear mixed models (GLMMs) analyses were performed instead with either the summed location or the summed movement direction scores treated as a binomial variable with a logit link function. Generalized linear mixed models (or GLMMs) can be conceived of as a generalization of standard repeated measures analysis of variance models where the dependent variable is not necessarily continuous and normally distributed, but can also be a binary or binomial response, see for example Stroup (2013) for details.

3.3. Results

Overall, participants were very good at determining the location and direction of cars, accuracy being 93.2% and 91.4% respectively.

3.3.1. Hearing loss

The GLMM analysis showed no main effect of hearing loss on location and movement direction decisions. Descriptive analysis revealed that both location and movement direction scores of participants without hearing loss were clustered more around the high end of the scale (see *Figure 3.3a* and *b*).

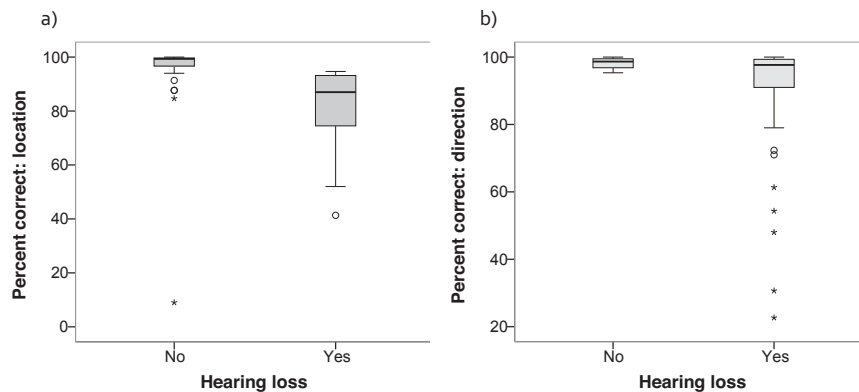


Figure 3.3. Boxplots depicting the spread of the mean percentage of correctly localised cars (pooled for speed, car type, movement direction and ambient sound level): in terms of location decisions (pooled for location) (a) and movement direction (approaching and receding pooled) for participants with and without hearing loss (b). Boxplots show median (line), lower and upper quartiles (box), total range (whiskers), outliers (°) and extreme outliers (*).

Whilst almost all participants without hearing loss had high location and movement direction scores, some participants with hearing loss were impaired and some were not.

3.3.2. Car type and speed

Main effects for car type ($F(1, 57) = 28.59, p < .001$) and speed on location decisions were found ($F(2, 200) = 22.80, p < .001$). Conventional cars elicited more correct location decisions than electric cars and cars driven at 15 km/h elicited fewer correct location decisions than those driven at 30 km/h ($t = 5.43, p < .001$) or 50 km/h ($t = 6.42, p < .001$) (consistent with hypothesis 1 and 2) (see *Figure 3.4a*). A significant interaction effect between car type and speed was also found ($F(2, 5436) = 5.83, p = .003$) (consistent with hypothesis 1). In *Figure 3.4a* we can see that the difference in average percentage of correct answers between electric and conventional cars is much larger at 15 km/h than at the two other speeds.

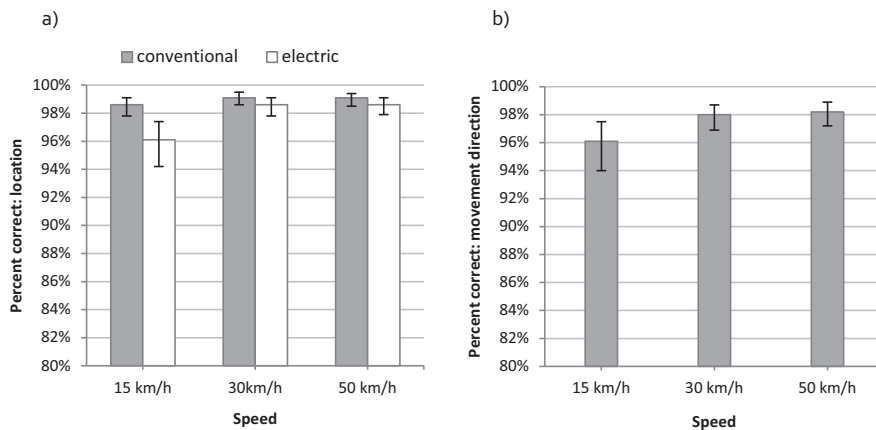


Figure 3.4. Estimated mean location percentages (a) and mean movement direction percentages (b) for car type and age groups. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

There was no difference between conventional and electric cars regarding movement direction decisions (no main effect of car type, inconsistent with hypothesis 1). A main effect for speed was found (consistent with hypothesis 2) ($F(2, 94) = 34.87, p < .001$): cars driven at 15 km/h elicited fewer correct movement direction decisions than those driven at 30 km/h ($t = 2.78, p = .01$) or 50 km/h ($t = 2.78, p = .01$; see also *Figure 3.4.b*). No interaction effect between car type and speed was found (inconsistent with hypothesis 1).

3.3.3. Movement direction: approaching versus receding cars

The location of receding cars was more often correctly identified than approaching cars $F(1, 77) = 29.3, p < .001$ (inconsistent with hypothesis 3), but the movement direction of receding cars was less often correctly identified than that of approaching cars $F(1, 57) = 8.47, p = .005$ (consistent with hypothesis 3) (see *Figure 3.5a* and *b*).

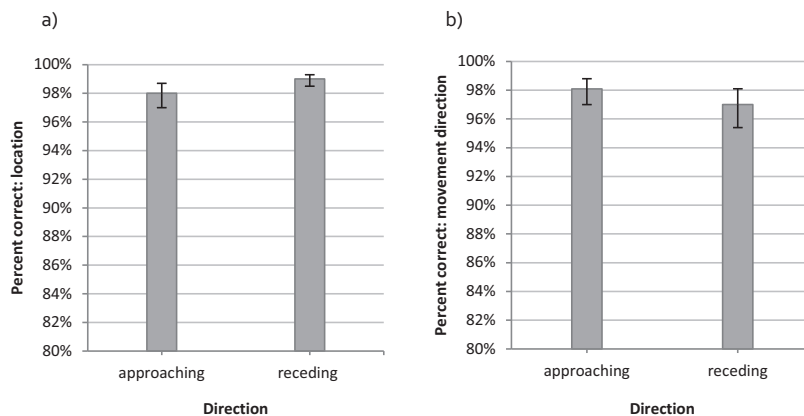


Figure 3.5. Estimated mean location percentages (a) and mean movement direction percentages (b) for approaching and receding cars. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

3.3.4. Location

The loudspeaker from which the car sound was coming affected the location decisions (main effect of loudspeaker), $(F(1, 57)=28.59, p < .001)$: sounds coming from loudspeaker 4: right behind the listener elicited the lowest location scores: significantly lower than loudspeaker 2 ($t = 3.64, p < .001$), loudspeaker 5 ($t = 2.36, p = .02$), loudspeaker 6 ($t = 3.45, p < .001$) and loudspeaker 7 ($t = 2.41, p = .02$) (see *Figure 3.6*) (partly consistent with hypothesis 4). No effect of location from which the car sound was coming on movement direction decisions was found (inconsistent with hypothesis 4).

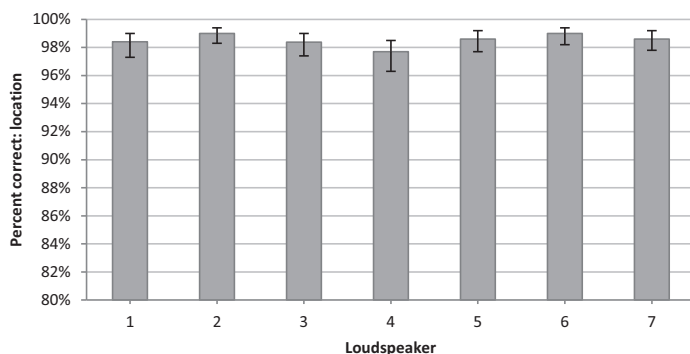


Figure 3.6. Estimated mean location percentages for loudspeaker. The numbers correspond to the position of the loudspeakers shown in *Figure 3.2*. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

Descriptive analysis showed that half of all errors (3.4% of all responses) was related to participants not choosing any answer option and the other half related to choosing a wrong loudspeaker, most often a loudspeaker positioned on the same side (left, right) (36.6% of all errors). There was also a number of front-back confusions (8.5% of all errors): car sounds from the front (from speaker 1 or 7) were incorrectly perceived as coming from the back (from speaker 3 or 5), and the other way round. Loudspeaker 4 was more often mistaken with the adjacent rear speaker on the right (speaker 3; 5.3% of all errors) than on the left (speaker 5; 2.3% of all errors), but it was also confused with speakers in the front (speaker 1 or 7; 2.3% of all errors) (see also *Table 3.2*).

Table 3.2. Distribution of location scores (in percentages); SP = speaker.

Response								No response	Total
<i>Sound location</i>	SP1	SP2	SP3	SP4	SP5	SP6	SP7		
SP1	92.82	2.35	1.20	0.13	0	0	0.04	3.46	100
SP2	0.43	94.62	1.20	0.09	0.04	0	0.09	3.55	100
SP3	0.64	3.21	92.56	0.13	0	0.04	0.04	3.38	100
SP4	0.51	0.09	2.52	91.28	1.07	0.17	0.60	3.76	100
SP5	0	0	0.09	0.34	93.29	2.05	0.47	3.76	100
SP6	0	0.04	0.04	0.13	2.31	94.62	0.17	2.69	100
SP7	0	0.04	0.04	0.04	1.71	1.58	93.59	2.99	100

3.3.5. Age groups

A main effect of age was found for both location $F(2, 69) = 22.20, p < .001$ and movement direction decisions $F(2, 59) = 8.79, p < .001$. Older adults had significantly lower location scores than middle aged ($t = 4.72, p < .001$) or adolescent participants ($t = 4.10, p < .001$) and significantly lower movement direction scores than middle aged ($t = 3.78, p < .001$) or adolescent participants ($t = 2.63, p = .01$) (see *Figure 3.7a* and *b*) (consistent with hypothesis 5).

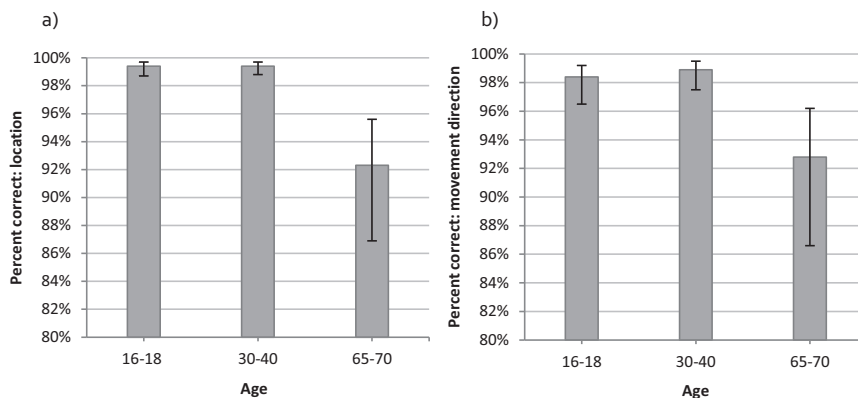


Figure 3.7. Estimated mean location percentages (a) and mean movement direction percentages (b) for age. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

To further investigate whether specific conditions were particularly difficult for older adults, interaction effects were also examined. For location decisions no interaction effects between age and either car type, speed, condition or direction (approaching versus receding) were found. However, an interaction effect was found for movement direction decisions between age and speed $F(4, 82) = 5.35, p = .001$. *Figure 3.8a* shows that the difference in average percentage of correct answers between the 15 km/h and the 50 km/h speed condition is larger amongst teenage participants than amongst the two adult groups (see *Figure 3.8a*).

Furthermore, a significant interaction effect was also found between direction and age $F(2, 55) = 5.99, p = .004$. In *Figure 3.8b* we can see that, contrary to teenage and middle-aged participants, older adults were more accurate about the direction of receding cars than of approaching cars. No interaction effect for movement direction decisions was found between age and car type or condition.

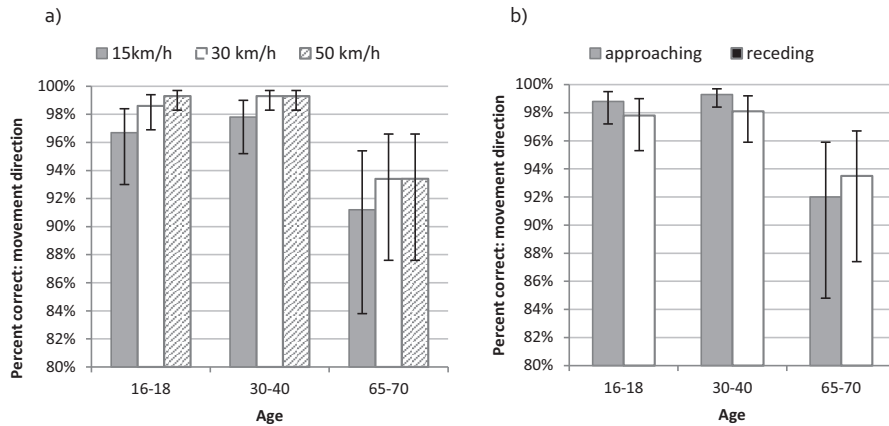


Figure 3.8. Estimated mean movement direction percentages for approaching and receding cars (a) and for speed (b) per age groups. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

3.3.6. Ambient noise

Location decisions were significantly more accurate when the cars were presented in low ambient sound than in moderately noisy ambient sound (consistent with hypothesis 6) $F(1, 63) = 12.05, p = .001$ (Figure 3.9a).

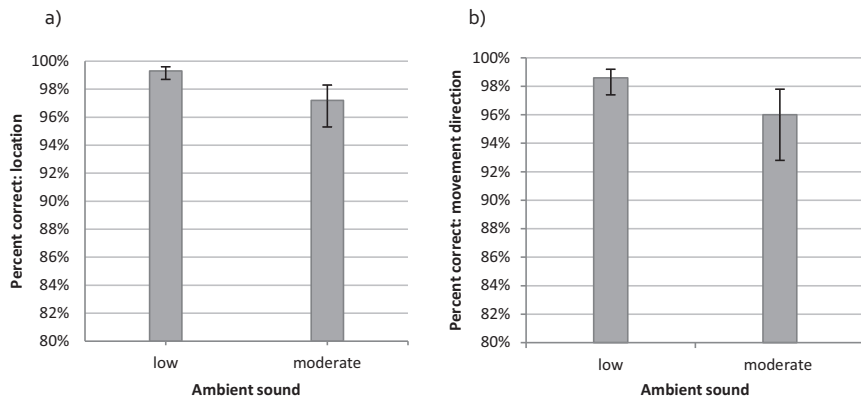


Figure 3.9. Estimated mean location percentages (a) and movement direction (b) for ambient sound level. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

Movement direction decisions (about whether the car was approaching or receding) were significantly more accurate when the vehicles were presented

in low ambient sound then in moderately noisy ambient sound (in line with hypothesis 6) $F(1, 57) = 7.01, p = .001$ (Figure 3.9b).

3.4. Discussion

The current study explored localisation decisions of conventional and electric cars approaching a cyclist from and receding in various directions. In general, results show that it is more difficult to discriminate the location of electric cars than that of conventional cars. Furthermore, location and motion direction decisions were less accurate for cars at low speed and for higher ambient sound level. We also found that older adults obtained the lowest localisation scores. Finally, the location discrimination of car sounds directly behind was the lowest. In this section, we discuss the results within the context of previous literature.

3.4.1. Car type and speed

As expected (hypothesis 1), the location of electric cars was less often correctly identified than the location of conventional cars. The results of this study show also, consistent with our hypothesis (2) that the localisation accuracy is affected by the speed of the car. Cars driven at 15 km/h were localised less accurately than those driven at 30 km/h or 50 km/h. An interaction effect has been found between car type and speed: electric cars driven at low speeds (15 km/h) elicited the lowest location scores. This finding is consistent with detection studies which show that at low speeds hybrid and electric cars are detected later than conventional cars (e.g. Garay-Vega et al., 2010; JASIC., 2009; Kim et al., 2012a).

A localisation study by Barton, Ulrich & Lew (2012), exploring the identification of cars approaching from the left and from the right, shows similar effects for speed: the localisation of cars was less accurate for vehicles driven at lower speeds (8 km/h) than at higher speeds (19, 40 or 56 km/h). In that study only conventional vehicles were used. In the current study, both location and movement direction decisions were affected by car speed. Car type however, influenced only location decisions. Faster cars and conventional cars generally emit more sound than slower and hybrid or electric cars and are therefore better identified and localised (e.g. Barton, Ulrich & Lew, 2012; Garay-Vega et al., 2010; JASIC., 2009). This study suggests that location decisions are more sensitive to acoustic characteristics of a car than direction movement decisions.

Contrary to previous studies comparing the localisation of conventional and hybrid electric cars without add-on sounds (Kim et al., 2012b; Wall Emerson et al., 2011a), this study found no differences in localisation accuracy between the two car types. This contradiction could reflect differences in motion paths and sample population between previous studies and the present one. Kim et al. and Wall Emerson et al. performed their studies amongst visually impaired participants. Furthermore in previous studies only two pathways different to those in the current study were used: a straight parallel path to the left of the listener and a path turning right. The current study used seven straight paths towards the listener and no turning paths. Finally, in the studies of Kim et al. and Wall Emerson et al. the cars approached, came to a full stop approximately 1.2–2 m behind the listener and from that position proceeded either straight or turned right. This distance is much less than the various motion paths in our study (23–76 m depending on the car speed).

3.4.2. Location

We found that it was more difficult to indicate from which location the car sound was coming when it was presented directly behind the listener. This confirms our hypothesis 5. The difficulty with car sounds coming from behind may be caused by the absence of binaural cues: for sounds directly behind the head the sound intensity and arrival time in each ear is the same (e.g. Grothe, Pecka & McAlpine, 2010). To our knowledge this is the first study exploring localisation accuracy of cars approaching and receding in various directions in which directions directly behind the listener were included.

3.4.3. Direction

One unexpected result of our study was that the location of receding sounds was more often correctly determined than that of approaching cars. Based on fundamental research showing environmental salience (the ability to perceive and respond to rapidly approaching objects can, after all, have life or death consequences) of looming sounds and the priority with which they are perceptually processed (e.g. Fabrizio et al., 2011; Neuhoff, Long & Worthington, 2012; Neuhoff, Planisek & Seifritz, 2009; Seifritz et al., 2002; Von Mühlennen & Lleras, 2007), our hypothesis was the opposite (hypothesis 6).

To our knowledge there are no studies into auditory localisation of looming versus receding traffic sounds. The perceptual priority of looming sounds may be limited to only some aspects of auditory perception, such as distance perception, and may not necessarily apply to auditory localisation. It is also

possible that the assumed inconsistency between fundamental research and the current study is related to the various acoustic characteristics of the sounds used in the studies (e.g. a square wave versus car sound) or to the differences in methodology (e.g. presentation of sounds via headphones versus via loudspeakers). On the other hand, the movement direction of approaching cars was more often correctly identified than that of receding cars, except for the elderly. More research is needed to clarify these findings.

3.4.4. Age and hearing loss

As hypothesised (hypothesis 4) older adults exhibited less localisation accuracy than teenage and middle-aged participants. Age-related differences have been reported by earlier studies into auditory perception of moving cars (Barton et al., 2013; Mendonça et al., 2013; Pfeffer & Barnecutt, 1996) and by studies into localisation of static sounds (Briley & Summerfield, 2014; Dobрева, O'Neill & Paige, 2011). The current study is, to our knowledge, the first one showing impairment in localisation of moving cars by older adults. Briley and Summerfield (2014) suggested that localisation deficits associated with older age could reflect both peripheral and central impairments, such as high-frequency hearing loss or decline in temporal processing.

Hearing loss in the present study was comprised of a variety of types (various frequencies, degree, unilateral versus bilateral). We found that almost all participants without hearing loss had high localisation scores, whilst only some participants with hearing loss were impaired on the task. This finding suggests that there may be some specific types of hearing loss affecting the auditory localisation of cars in motion. The diminished ability of older adults to localise static sounds could also reflect typical auditory disabilities associated with older age, such as difficulty in locating and tracking the sources of sound for which central processing is required. This assumption is supported by the study of Otte et al. (2013), in which the ability to localise static sounds by older adults with subsequent high-frequency hearing loss was only affected in the vertical plane, but not in the horizontal plane. The subcortical processing of binaural ITD and ILD cues, required for the horizontal localisation of static sounds, may be less affected by increasing age than more complex auditory processing like tracking sources of sound (that is, moving vehicles).

Future studies should explore the mechanisms underlying age-related deficits in the localisation performance of moving sound objects. Gaining insight into the constraints of human auditory perception of traffic sounds at different

developmental stages is important to develop countermeasures to protect cyclists and other road users, who, at least in some situations, rely on auditory information to navigate the traffic environment.

3.4.5. Ambient sound level

Previous research showed that ambient sound level is a strong predictor of how early vehicles are detected (Garay-Vega et al., 2010; JASIC., 2009). If the ambient sound level is high, as in most urban areas, the sound coming from individual cars is masked by other sounds (especially when the other sounds contain frequencies equivalent or similar to those of the target sound). Detectability studies show that in higher (above approximately 50 dB; Wall Emerson & Sauerburger, 2008) ambient sound levels, it is not possible for pedestrians to hear vehicles soon enough to enable safe crossing.

The present study shows, consistent with our hypothesis 3, that localisation of cars in motion is more difficult in moderately noisy ambient sound (53 dB-A) than in low ambient sound (44–45 dB-A). Apparently for some vehicles correctly localised in low ambient sound, the signal-to-noise ratio in moderately noisy ambient sound was too high to enable accurate localisation. The results are also in line with fundamental research. Dobreva, O'Neill, and Paige (2011) demonstrated that sound localisation deteriorated for stimuli at near-threshold levels (very soft sounds near the threshold of hearing), which suggests that it becomes harder to localise quiet cars.

3.4.6. Implications for cycling safety

Although vision and visual attention are crucial for the safe management of road hazards, auditory cues are also important for cyclists. Auditory information can act as an attentional trigger and can facilitate detection and localisation of other road users. In this context, some implications for cycling safety can be drawn from the present study. Those implications are potentially greater in situations where cyclists cannot rely on visual information, e.g. for gathering information outside one's field of view or when visibility is obscured.

To start with, it is worth mentioning that although the reported localisation differences found in this study are small, the consequences of not being able to detect and localise approaching cars in time can have severe, even fatal, consequences for a cyclist. The present study adds to the findings of detectability studies, showing that the concerns regarding the sound emissions of electric vehicles should be taken seriously. Previous studies showed that, when driven at low speeds, electric cars are detected later than conventional ones.

This study found that slow-moving electric cars are less often correctly localised than conventional cars travelling at the same low speed. Slower speeds are generally thought to be safer for vulnerable road users. In a collision between a car and a cyclist or pedestrian, the survival rate of the vulnerable road user decreases enormously as the car impact speed increases (Rosén, Stigson & Sander, 2011; Tefft, 2013). However, even at low car speeds, collisions can still have serious consequences for cyclists, especially for the elderly.

The elderly run a relatively high risk of dying or sustaining serious injuries as a result of a cycling crash (Davidse, 2007; Evans, 2001). One factor which plays a role is their relatively high vulnerability. In an accident, a senior cyclist runs a high risk of fracturing a hip or leg (Weijermars, Bos & Stipdonk, 2016). Electric vehicles can be expected to pose a safety threat particularly for the elderly due to their vulnerability and the difficulty this age group has with detection (Mendonça et al., 2013) and localisation (as shown in this study) of electric vehicles.

To improve detectability of hybrid and electric cars, equipping these vehicles with artificial sound has been proposed (GRB, 2013; NHTSA, 2013). Some government agencies (e.g. in Japan, the US, European Parliament) are working on standards for a minimum sound level emitted by vehicles (European Parliament, 2013). Add-on sounds may potentially provide some improvement in the detectability of electric cars, however at the cost of increased noise levels. To be effective in various ambient sound levels, the increased sound level will have to be quite high and thus unacceptable in urban situations (Yamauchi et al., 2010). Furthermore, the problem of low detectability will remain for some cars: in the new ambient sound levels, some cars will still be too silent.

From a traffic safety perspective, negative effects may also appear, that is negative behavioural adaptation by drivers. Behavioural adaptation describes the collection of behaviours that occurs following a change to the road traffic system or specific road safety measures (Rudin-Brown & Jamson, 2013). For example, in the presence of an artificial sound drivers may expect vulnerable road users to be able to hear the car and therefore may not drive as carefully as they would without the added sound (Sandberg, 2012; Sandberg, Goubert & Mioduszewski, 2010).

Other solutions to the problem of low detectability have been proposed, for example using cobbled pavements in low-speed traffic environment (Mendonça et al., 2013), public campaigns, pedestrian/cyclist detection systems and systems informing cyclists about the presence of a (quiet) vehicle (Ashmead et al., 2012; Blauert, 1997; Mendonça et al., 2013). The non-acoustical solutions, although challenging (the full range of cyclists need to be provided with accurate, timely information) are highly valued as they allow for environmental improvements, in particular the noise reduction offered by quiet (electric) cars. Future studies should explore the suitability of these solutions from the perspective of traffic safety.

Interestingly, a recent study suggests that drivers can mitigate the potential risks resulting from low sound emissions from their cars (Cocron et al., 2014). In laboratory conditions both drivers who had experience with driving an electric car and drivers with no such experience were found capable of detecting and responding adequately to noise-related hazards involving vulnerable road users (cyclists, pedestrians, a jogger). However, due to various limitations of the study (e.g. reduced external validity), these results do not allow firm conclusions about the utility of warning systems in hybrid and electric cars.

The present study also showed that the auditory localisation of car sounds directly behind the listener is less accurate than the localisation of cars sounds coming from other directions. This difficulty is presumably related to the lack of binaural cues, and therefore increasing the sound level of quiet cars will most likely not help cyclists to localise cars coming from this location. Bicycle educational programs and trainings should emphasize the importance of visual inspection of areas behind the cyclist when checking the location of approaching traffic. In the future, technological solutions to improve the detectability of cars, mentioned above, may prove more effective in assisting cyclists with the localisation of cars in motion.

It is worth mentioning that transition periods, during which vulnerable road users have to deal with a mix of vehicles varying in conspicuity, are potentially difficult and risky. When quiet hybrid and electric vehicles constitute a substantial share of the total fleet, cyclists (and pedestrians) will probably be more aware of their potential presence and behave accordingly. Cyclists may, for example, eventually learn to rely less on auditory information and to compensate for the limited auditory input, by for example increasing visual attention. Indeed, a recent study by (Ahlstrom et al., 2016) showed that cyclists applied compensatory strategies to adapt their gaze behaviour to the traffic situation. Specifically, when operating a mobile phone, cyclists' glances towards the phone were at the expense of glances towards traffic irrelevant targets (for example trees, birds or advertising signs).

3.4.7. Limitations

As with every study, this study also had some limitations that have to be discussed. Firstly, the sound of only one electric car was used in this study. The results may therefore not generalise to other electric cars. As such, the results of these studies show that some electric cars may be more difficult to localise than conventional cars. As various models of hybrid and electric vehicles differ in terms of acoustic output (Garay-Vega et al., 2010; Morgan et al., 2011), future studies should use a greater variety of electric car sounds comprising cars of different sizes.

Secondly, due to the great number of trials in the experiment and the nature of the task, some participants, especially older adults, may not have maintained focused attention during the whole experiment. Although participant fatigue cannot be excluded, we believe its effects were more limited than extensive. Participants were offered regular breaks. Furthermore none of the participants reported fatigue or discomfort either during or after the experiment.

Thirdly, the issue of external validity merits further attention. Unlike participants in this study, cyclists typically move around engaging in various manoeuvres. Therefore the cognitive demands associated with actual cycling (being in motion and having to navigate safely through the traffic environment) are higher than in our laboratory setting. Additionally, due to the fact that cyclists move around, their perception of car sounds in real traffic, may differ somewhat from the perception of stationary listeners. The resemblance between the auditory perception of our participants and that of cyclists in real traffic is potentially greater in situations in which cyclists ride

very slowly, or are stationary. Furthermore, the sound stimuli used in this study did not include other types of ambient sounds (such as wind noise, aerodynamic noise caused by the head of a cyclist moving through the air, people talking on the sidewalk or other loud masking noises), which are typically present in real traffic situations. The influence of these competing factors was deliberately controlled for in this study to investigate the influence of the variables of interest.

Due to reduced external validity, our study may not provide normative data into the auditory localisation of cars in motion. It is expected that the reality of navigating through traffic with various ambient sounds would make auditory localisation more difficult for cyclists than for the participants in our laboratory setting. Finally, in this study the influence of other relevant factors such as traffic volume, road surface, weather condition, or sound reflection has not been examined either.

3.4.8. Directions for future research

To enhance external validity, we recommend that future research into the auditory localisation of vehicles by cyclists be conducted in real traffic settings. Based on the results of the present study, future research could focus on auditory localisation in selected, critical safety scenarios, that is, traffic environments where various vehicles are driven at low speeds with a moderately noisy ambient sound level.

Given the popularity of electronic portable devices amongst cyclists, examining auditory localisation whilst cycling and listening to music or conversing on the phone is warranted. A field experiment by De Waard, Edlinger, and Brookhuis (2011) showed that auditory detection of bicycle bells deteriorated when cyclists were engaged in these secondary activities. High tempo music, loud music and in particular music listened to through in-earphones was found to impair the hearing of loud sounds, that is, horn honking. Since listening to music and talking on the phone restricts the auditory perception of cyclists, engaging in these activities can be expected to compromise auditory localisation.

An important aspect to explore is whether listening to music through one earphone is a safe option for cyclists. Although this way of listening to music does not seem to affect the detection of auditory stimuli (De Waard, Edlinger & Brookhuis, 2011), it may compromise the localisation of sounds in space for which input from both ears is needed (Baldwin, 2012). In this case, listening to

music with one earphone may also pose a safety hazard. Besides localisation accuracy, future studies may also wish to explore localisation latency and relate the time needed for a cyclist to localise a relevant vehicle in motion to the general time needed to perform a specific cycling manoeuvre.

Finally, the fact that auditory detection and the localisation of car sounds is impaired in some situations, has, according to the model of Endsley (1995) consequences for situation awareness. These consequences are potentially greater in situations where cyclists rely on auditory information (obscured visibility, traffic approaching from behind, etc.). Future studies might focus on how auditory perception aids visual perception in facilitating cyclists' situation awareness.

4. Impact of mobile phone conversations, listening to music and quiet (electric) cars on cyclists' auditory perception and involvement in traffic incidents ¹³

As shown in *Chapter 2*, it is unknown whether restricted auditory perception among cyclists, contributes to a higher risk of crashes. Therefore, this chapter investigates to what extent cyclists' auditory perception and involvement in road traffic incidents are affected by quiet vehicles, listening to music or phoning while cycling. This investigation is based on self-reported data from cyclists in three age groups (teenagers, adults and older adults) and includes an exploration of cyclists' use of strategies to compensate for the lack of auditory cues.

Section 4.1 provides background information including relevant previous research and presents the rationale for the study. An online methodology was used to obtain data. The details of the methods used are presented in *Section 4.2*. In particular, this section describes the survey sampling and administration, questionnaire design and data analysis. *Section 4.3* reports the results for the three age groups of cyclists on their use of devices, involvement in compensatory behaviours, auditory perception and encounters with quiet vehicles. Furthermore this section presents results concerning cyclists' involvement in crashes and the relationship between listening to music or phoning and incidents. *Section 4.4* discusses the findings and their implications for cycling safety. This section ends with some concluding remarks.

¹³ This chapter was first published in *Accident Analysis & Prevention: Stelling-Konczak, A., Van Wee, G.P., Commandeur, J.J.F., Hagenzieker, M., (2017). Mobile phone conversations, listening to music and quiet (electric) cars: Are traffic sounds important for safe cycling? Accident Analysis & Prevention, vol. 106, p. 10-22.*

ABSTRACT Listening to music or talking on the phone while cycling as well as the growing number of quiet (electric) cars on the road can make the use of auditory cues challenging for cyclists. The present study examined to what extent and in which traffic situations traffic sounds are important for safe cycling. Furthermore, the study investigated the potential safety implications of limited auditory information caused by quiet (electric) cars and by cyclists listening to music or talking on the phone. An Internet survey among 2249 cyclists in three age groups (16–18, 30–40 and 65–70 year old) was carried out to collect information on the following aspects: 1) the auditory perception of traffic sounds, including the sounds of quiet (electric) cars; 2) the possible compensatory behaviours of cyclists who listen to music or talk on their mobile phones; 3) the possible contribution of listening to music and talking on the phone to cycling crashes and incidents. Age differences with respect to those three aspects were analysed. Results show that listening to music and talking on the phone negatively affects perception of sounds crucial for safe cycling. However, taking into account the influence of confounding variables, no relationship was found between the frequency of listening to music or talking on the phone and the frequency of incidents among teenage cyclists. This may be due to cyclists' compensating for the use of portable devices. Listening to music or talking on the phone whilst cycling may still pose a risk in the absence of compensatory behaviour or in a traffic environment with less extensive and less safe cycling infrastructure than the Dutch setting. With the increasing number of quiet (electric) cars on the road, cyclists in the future may also need to compensate for the limited auditory input of these cars.

4.1. Introduction

For a cyclist auditory perception can be of great importance, especially for gathering information from areas outside his/her field of view, or when visibility is obstructed. Auditory cues, such as tyre and engine noises, may help to detect and localise approaching road users and orient cyclists' visual attention towards oncoming traffic. Recently, the use of auditory information by vulnerable road users, such as cyclists and pedestrians, may have become more challenging due to the growing number of electric (and hybrid) cars on the road. Electric cars are still relatively rare on our roadways. However, their number is expected to increase sharply as many European countries set ambitious sales or stock targets for electric cars in the near future (OECD/IEA, 2016). When driven at low speeds, cars in electric mode are generally quieter than conventional cars, especially in the built-up area where engine noise dominates. Slow moving (hybrid) electric cars are also detected later and localised less accurately by vulnerable road users than conventional cars, especially in environments with low ambient noise (Stelling-Kończak, Hagenzieker & Van Wee, 2015). Furthermore, electric cars driven at low speeds are localised less accurately than conventional cars, as found in a recent laboratory study including vehicle motion paths relevant for cycling activity (Stelling-Kończak et al., 2016). Also studies with drivers of electric cars suggest

that cyclists have problems hearing these vehicles (Cocron & Krems, 2013; Hoogeveen, 2010). None of the drivers participating in these studies reported a noise-related crash. However, a substantial percentage of drivers (45% in the study of Hoogeveen and 67% in the study of Cocron & Krems) reported noise-related incidents, especially at low speeds, e.g. pedestrians and cyclists missing the electric car or getting startled or surprised by its approach.

Besides electric cars, the increasing use of mobile technology while cycling can also make it more difficult for cyclists to utilize auditory cues. A field study by de Waard et al., (2011) has shown that listening to music and talking on the phone impairs cyclists' perception of relevant traffic sounds such as the sound of a bicycle bell. In this study high tempo music, loud music and in particular music listened through in-earphones has been found to impair even hearing of loud sounds, that is, horn honking. Talking on the phone and listening to music are quite popular among cyclists, especially youngsters. In a Dutch survey, 76% of the teenage cyclists but only 14% of the cyclists older than 50 years old reported listening to music. In the same study, 77% of the teenage cyclists and 34% of the older cyclists reported using a mobile phone while cycling (Goldenbeld et al., 2012).

The role of auditory information in cycling has only recently become the topic of scientific research. According to the conceptual model of Stelling-Konczak, Hagenzieker & van Wee (2015), restricted auditory perception can have consequences for cycling safety (see *Figure 4.1*). Being unable to hear traffic sounds can negatively affect cyclists' situation awareness¹⁴ and cycling performance. In the presence of traffic-related hazards, a degraded cycling performance can in turn lead to crashes if it is not sufficiently compensated by the cyclist himself or other road users involved. The conceptual model in *Figure 4.1* also acknowledges the importance of cyclist characteristics (biological, sociocultural, traffic-related and temporary factors) and of the traffic environment (e.g. road infrastructure, weather, traffic-related conditions) when studying the relationship between restricted auditory perception and cycling safety.

¹⁴ Situation awareness refers to the awareness of the meaning of dynamic changes in the environment (Endsley, 1995), e.g. the awareness of approaching vehicles.

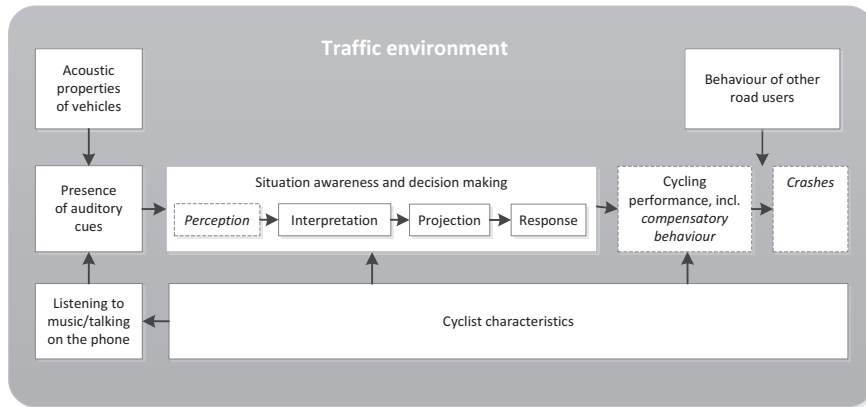


Figure 4.1. Conceptual model of the role of auditory information in cycling safety (adapted from Stelling-Kończak, Hagenzieker & Van Wee, 2015). Knowledge gaps are marked by dashed boxes.

To date, little research has been done into the impact of device use while cycling or of the quietness of electric cars on cycling safety. In their review article Stelling-Konczak et al., Hagenzieker & van Wee, (2015) identify a number of important knowledge gaps which need to be addressed for a better understanding of the relationship between limited auditory information and cycling safety.

To begin with, little is known about the auditory perception of cyclists who listen to music or talk on the phone. Phone conversation and music was found to deteriorate the detection of traffic sounds, i.e. the sound of a bicycle bell and a horn honking (De Waard, Edlinger & Brookhuis, 2011). There are two potential explanations for these negative effects. Music and telephone conversation may cause distraction by diverting attention away from the traffic task toward inward experiences (thoughts, memories, emotions, moods) (see for example Herbert, 2013; Strayer et al., 2013). The other explanation concerns auditory masking: the phenomenon that occurs when one sound (e.g. music or speech) prevents or blocks the perception of another sound (e.g. a sound of an approaching car). Auditory masking is a complex phenomenon and the potential of a sound to be masked depends on the frequency and intensity of that sound (see e.g. Baldwin, 2012). Given the complexity of the masking phenomenon, the results of prior research into cyclists' auditory perception do not allow conclusions about the influence of listening to music or talking on the phone on the perception of other traffic

sounds such as the sounds of cars, whether they be conventional or electric cars.

Next, not much is known about the potential compensatory behaviour of cyclists who listen to music or talk on the phone. In the only study that we could find, an Internet survey by Goldenbeld et al. (2012), two-third of the cyclists reported adjusting their behaviour when using portable devices. The most popular type of compensatory behaviour among older cyclists was wearing a bicycle helmet and refraining from using portable devices in demanding traffic situations. Younger cyclists reported compensating for the use of devices mainly by paying more attention to traffic. Compensatory behaviour in that study was examined for device use in the aggregate (consisting of listening to music, having a phone conversation, texting and searching for information). We therefore do not know to what extent cyclists specifically listening to music or talking on the phone engage in compensatory behaviour.

Furthermore, very little research has been done into the impact of device use or the quietness of electric cars on cyclists' crash involvement. The only study into the effect of mobile devices on cyclists' crash risk we have been able to find (Goldenbeld et al., 2012) showed that using a mobile device was associated with an increased risk of self-reported bicycle crash involvement. The study controlled for the influence of a number of cyclist characteristics and factors in the traffic environment (i.e. age, urbanization, cycling time, and cycling in demanding situations). The overall risk of a self-reported crash for cyclists who used electronic devices on every trip was found to be a factor 1.6 higher for teenagers and a factor 1.8 higher for young adults compared with their respective age counter-parts who never used devices while cycling. Apparently the compensatory behaviour of young cyclists is not sufficient to counterbalance all the risks associated with the use of electronic devices. The crash risk of individual tasks was not examined in that study and thus remains unknown. Some individual tasks may pose a higher safety risk than others. Texting and searching for information are activities that do not require auditory but mainly visual perception and attention, and are considered riskier than listening to music or talking on the phone.

As concerns electric cars, their safety performance cannot be easily compared to that of conventional cars, primarily due to the lack of exposure data (i.e. kilometres travelled) for both car types. Some studies show higher incidence

rates¹⁵ of crashes involving hybrid or electric cars and vulnerable road users (Hanna, 2009; Morgan et al., 2011; Wu, Austin & Chen, 2011). However, as these incidence rates are not corrected for exposure, there is no evidence that hybrid or electric cars pose a higher safety hazard for pedestrians and cyclists than conventional cars (see Verheijen & Jabben, 2010).

4.1.1. This study

The present study addresses the three aforementioned research gaps in the relationship between limited auditory information and cycling safety. A sample of over 2200 respondents in three age groups (teenage, adult and older cyclists) completed an Internet survey. The teenagers and the elderly were the main focus of the study, as these age groups are particularly vulnerable in terms of cycling safety. In the EU countries, cyclists of 65 years and older represent a large proportion of cyclist fatalities (37%). There is, furthermore, a peak in fatalities among teenage cyclists of 12–17 years old, the age of increasing cycling autonomy (Candappa et al., 2012). Older and teenage cyclists are also of interest from the perspective of the auditory perception of traffic sounds: young cyclists because of their frequent use of devices, the elderly due to the decline in hearing abilities in old age (e.g. Schieber & Baldwin, 1996; Van Eyken, Van Camp & Van Laer, 2007).

Our study has three aims. The first objective was to explore self-reported auditory perception of traffic sounds, including the sounds of quiet (electric) cars, among cyclists of the three age groups. As listening to music and talking on the phone were found to impair the hearing of a bicycle bell (De Waard, Edlinger & Brookhuis, 2011), we could expect that cyclists' perception of other traffic sounds, e.g. the sounds of cars (especially quiet electric cars) will at least to some extent be compromised by listening to music or talking on the phone. As electric cars are still quite rare on Dutch roads we expected that cyclists would probably not have much experience with the auditory characteristics of these cars. The second aim was to examine to what extent cyclists in the three age groups compensate for listening to music or talking on the phone. Based on earlier research (Goldenbeld et al., 2012), we expected age differences in the frequency of listening to music and talking on the phone as well as in the reported compensatory behaviour.

¹⁵ Incidence rates = the number of vehicles of a given type involved in crashes with a pedestrian or bicyclist divided by the total number of that type of vehicle that were involved in any crashes.

The third aim was to investigate for each age group the extent to which listening to music and talking on the phone impact cyclists' involvement in self-reported crashes and incidents. Listening to music or talking on the phone, although considered less dangerous than activities involving manual phone manipulation, may still pose a safety risk to cyclists. On the other hand cyclists may sufficiently compensate for these risks by adapting their behaviour. While assessing the contribution of listening to music and talking on the phone to cycling crashes and incidents, we attempted to control for potentially risk-increasing cyclists characteristics and aspects of the traffic environment. The influence of two aspects of the traffic environment was taken into account, i.e. the time spent cycling and the exposure to complex traffic situations (i.e. cycling in darkness, etc.). These two aspects were chosen as they were found to be significant predictors of crash involvement among cyclists in the study of Goldenbeld et al. (2012). With regard to cyclist characteristics, sensation seeking and impulsivity have been found to correlate positively with both self-reported and police-recorded motor vehicle crashes (Dahlen & White, 2006; Iversen & Rundmo, 2002; Stevenson et al., 2001). This relationship is either direct or indirect, the relationship being mediated by risky driving behaviours in the latter case. Furthermore, a study with adult non-motorized road users (i.e. e-bike riders) has shown that risk perception, attitudes towards safety and responsibility are associated with risky riding behaviour (Yao & Wu, 2012). Given the length of the survey and the time commitment required to complete it, we investigated the effects of only two psychological determinants: risk perception and sensation seeking on the (self-reported) crash involvement of cyclists. At the same time, we also corrected for the influence of other risky cycling behaviour which may accompany listening to music or talking on the phone.

4.2. Methods

4.2.1. Survey sampling and administration

An online data collection procedure was considered well-suited in obtaining a representative sample of Dutch cyclists since more than 80% of Dutch inhabitants own a bicycle (CROW Fietsberaad, 2014) and 92% of Dutch households are connected to the Internet (European Commission, 2013). The survey was administered online between 13 and 30 June 2014 via a survey company that maintains an online panel of respondents. Data was collected from a total of 2249 respondents in three age groups: young (16–18 years old; $N = 748$), adult (30–40 years old; $N = 749$) and older cyclists (65–70 years old; N

= 752). Half of the respondents in each age group were female. Respondents were included if they cycled at least once a week and had no major hearing deficiencies. The sample was representative of the national Dutch population in terms of educational level and regional distribution. Since the respondents were recruited from the cycling population, they may not be representative for the average Dutch person in terms of cycling time (see also *Section 4.3.3*)¹⁶. The survey took about 20 minutes to complete.

4.2.2. Questionnaire

The questionnaire consisted of three parts. Part 1 contained questions about demographics, exposure and bicycle use in general and in demanding situations. The elicited cyclists' characteristics included gender, age, hearing abilities and the type of school they had attended or were still attending. Furthermore, respondents were asked about their helmet use, the type of bicycle they usually use and whether they cycle alone or accompanied by others. The time spent cycling was measured with two items: the average number of trips during an ordinary week and the usual time spent cycling during a trip. A composite scale bicycle use in demanding situations consisting of 6 items was used to measure the frequency of cycling in demanding traffic situations, specifically cycling: in darkness, through intersections, roundabouts or crossings of the road, in heavy traffic, while sharing the road with motor vehicles, in heavy bus/truck traffic, in heavy (light) moped traffic (answer options: 0 = *never*; 1 = *seldom*; 2 = *on some bicycle trips*; 3 = *on most bicycle trips*, 4 = *on all bicycle trips*).

Part 2 included questions about the use of electronic devices, auditory perception of traffic sounds and compensatory behaviour while using devices. The measurement items are detailed in *Table 4.1*. Respondents were asked about the frequency of device use, i.e. listening to music, talking on the phone, texting and searching for information on the phone while cycling in general and while cycling in more demanding traffic situations described above. Questions about texting and searching for information were asked to place the frequency of listening to music and talking on the phone in the

¹⁶ The average weekly amount of time spent cycling in the Netherlands is: about 201 min for teenagers 12–18 years old, 70 min for adults 30–40 years old and about 95 min for adults 65–70 years old (Fishman et al., 2015; Statistics Netherlands, 2016). Unfortunately no data is available on the average weekly amount of time spent cycling among the population of cyclists in the Netherlands.

Table 4.1. Items in Part 2 of the questionnaire.

Measures	Items	Answer options:
Use of electronic devices	How often do you: <ul style="list-style-type: none"> • listen to music • talk on the phone • text • search for information on the phone during an ordinary cycling week? while cycling in demanding traffic situations?	never/ seldom/ on some bicycle trips/ on most bicycle trips/ on all bicycle trips
	How do you usually listen to music? How do you usually talk on the phone?	2 earbuds/1 earbud/ 2 in-earbuds/1 in-earbud/ headphones/loudspeaker/alternating
Auditory perception	How much sound can you hear when: <ul style="list-style-type: none"> • you listen to music while cycling? • you talk on the phone while cycling? How much sound should a cyclist hear to be able to cycle safely?	nothing at all/ not much/ only loud or sharp sounds/ most sounds/ all sounds/ don't know
	How often do you encounter a quiet (electric) car while cycling? Do you know what an electric car sounds like?	never/ seldom/ on some bicycle trips/ on most bicycle trips/ on all bicycle trips/ don't know yes/no
Compensatory behaviour	What do you usually do when you get called when cycling?	I do not get called when cycling/ I answer the phone and I have a conversation / I answer the phone but I try to keep the conversation short/ I answer the phone to say that I will call back later/ I stop/get off my bicycle to answer the phone/I decline the phone call/ I ignore the phone call/ something else, please specify
	What do you usually do when they want to call someone when cycling	I make a phone call while cycling/ I wait until I reach my destination/ I stop/get off my bicycle to make a phone call/ I postpone a call until I reach a less busy location/ I choose a different route and I make a call while cycling/ something else, please specify
	Do you adapt your cycling behaviour when listening to music? Do you adapt your cycling behaviour when talking on the phone?	No, I do not adapt my behaviour/ Yes: (<i>more than one answer allowed</i>) - I look around more often (<i>M, P</i>); - I cycle more slowly (<i>M, P</i>); - I slow down when approaching an intersection or a complicated traffic situation (<i>M, P</i>) - I choose other routes (<i>M, P</i>); - I choose other cycling times (<i>M, P</i>) - I listen to music through 1 earbud instead of 2 (<i>M</i>); - I turn the volume down when necessary (<i>M</i>) - I keep the conversation short(<i>P</i>) - something else, please specify (<i>M, P</i>)
Are there any specific traffic conditions in which you choose not to listen to music? Are there any specific traffic conditions in which you choose not to talk on the phone?	No, I listen to music/talk on the phone irrespective of traffic situation/ Yes: (<i>more than one answer allowed</i>) - when the visibility on the road is decreased, - with bad weather; - when it is busy; - in complex traffic situations; - with unknown routes; - when I ride a heavy or unstable bicycle; - when I ride a bicycle which is too small, too large or not mine; - when I feel sick; - something else, please specify	

* *M*: options for 'listening to music'; *P*: options for 'talking on the phone'

perspective of other activities which electronic devices (smartphone) offer. Respondents had also to indicate the manner of listening to music and talking on the phone. To measure auditory perception respondents were asked to indicate how much they can hear when listening to music and talking on the phone while cycling and how much a cyclist should hear to be able to cycle safely. Additionally, the respondents were asked two questions about quiet, electric cars: how often they encounter a quiet (electric) car when cycling and whether they know what an electric car sounds like. Compensatory behaviour was measured by asking respondents what they usually do when they get called and what they usually do when they want to call someone when cycling. Respondents were also asked whether they adapted their cycling behaviour when listening to music and talking on the phone and if so to specify the type of behaviour. Furthermore, respondents were asked to indicate whether there were some specific traffic conditions in which they decided not to listen to music or to talk on the phone and if so to specify these conditions.

Part 3 contained questions about sensation seeking, risk perception, risky cycling behaviour and involvement in traffic incidents and crashes. Sensation seeking (i.e. the need for excitement and stimulation) was measured with the Dutch Impulsive Unsocialized Sensation Seeking (ImpSS) scale consisting of 19 forced-choice items with answer true or false and involving items concerning lack of planning, the tendency to act impulsively without thinking, experience seeking and the willingness to take risks for the sake of excitement or novel experience (Zuckerman, 1993; 1994). The Dutch version of the Sensation Seeking scale has been validated by e.g. Feij et al. (1997). The percentage of true scores out of the total number items was used for the analyses. A high score on the scale indicated a high level of sensation seeking. Risk perception was measured with 4 items (Rundmo & Iversen, 2004) regarding worry and insecurity about cycling-related injury and risk for the respondent himself or herself as well as for other cyclists (e.g. *'I feel unsafe that I could be injured in a bicycle accident'*; *'I am worried for others being injured in a bicycle accident'*). The worry and insecurity subscale was chosen since its relationship with risky traffic behaviour has been found to be stronger than the cognition-based risk perception (Rundmo & Iversen, 2004). Response options ranged from 1 = *does not apply to me at all* (low risk perception) to 6 = *strongly applies to me* (high risk perception). A mean score was constructed on the basis of the four items.

Risky cycling behaviour was measured with an adapted version of the Adolescent Road Behaviour Questionnaire (ARBQ) (Twisk et al., 2015). The

ARBQ, originally developed by Elliott and Baughan (2004), is based on Reason's classification of road user behaviour (Reason, 1990). Twisk et al. (2015) adapted the original ARBQ to study pedestrian and cyclist behaviour. Most of the items to measure risky cycling behaviour in the present study were selected from this modified Adolescent Road Behaviour Questionnaire. Instead of the full set of four types of risky behaviour used by Twisk et al., we only included the items measuring the following three types of risky behaviour: violations, errors and lack of protective behaviour. Violations are deliberate deviations from normal safe practice or socially accepted codes of behaviour while errors refer to failures of planned actions to achieve intended consequence (Reason, 1990). Lack of protective behaviour concerns the lack of behaviours deriving their effectiveness not from skilled interaction with traffic but from isolating the respondent from some form of risk (Elliott & Baughan, 2004). Two items relating to adolescent-specific behaviours were replaced by age-neutral items. Furthermore, some items concerning pedestrian behaviour were replaced by items specific to cycling behaviour. In the end, risky cycling behaviour was measured with a total of 24 items, consisting of three subscales. Each subscale comprised of 8 items. Responses to the items consisted of six-point Likert scales (with categories ranging from 1 = *never* to 6 = *always*).

With regard to traffic incidents respondents were asked whether they had got startled or surprised by some other road user in the past month (answer options: 0 = *no*, 1 = *once*, 2 = *more than once*, 3 = *often*), and if so to give some more details about the (most recent) case (such as the reason for getting startling, the type of road user involved and whether the respondents were listening to music or talking on the phone at that time). Crash involvement was measured using two items: a binary item on crash involvement in the past 12 months (*yes/no*) and an item on the number of crashes (if *no* was chosen the number of crashes was set to 0). Respondents who reported being involved in one of more crashes were asked further questions about the crash (in case of several crashes the most recent one): which type of bicycle they were cycling at that time, and which circumstances had preceded or accompanied the crash (such as '*I was just cycling*'; '*Visibility was poor*'; '*There was much environmental noise*'; '*The road user involved in the crash was very quiet so I did not hear them coming*'; '*I was talking on the phone*'; '*I was listening to music*'; '*I was talking to my fellow cyclist*'; '*I was texting*'; '*I was busy with/ distracted by something*', etc.).

4.2.3. Analysis

The reliability and internal consistency of the items measuring risk perception (4 items), sensation seeking (19 items), risky behaviour (24 items) and

exposure to demanding cycling situation (6 items) were assessed using Cronbach's alpha. Items with values of Cronbach's alpha equal to or larger than 0.70 were considered internally consistent (Kline, 1999). Moreover, to investigate whether empirical confirmation could be found for the hypothesis that the 24 items of the risk behaviour scale can be decomposed into the three distinct subscales Errors, Violations and Lack of protective behaviour (each consisting of 8 items) a categorical principal component analysis (CATPCA) was performed in SPSS treating all 24 items on an ordinal measurement level. CATPCA is a data reduction technique appropriate for numerical, ordinal and nominal variables. It is used to identify the underlying components of a set of items while maximizing the amount of variance accounted for in those items. With this technique, a spatial image is obtained where the respondents (called objects in CATPCA) are represented as points and the items are represented as vectors (Gifi, 1990). The closer points are located together, the more similar are the answer profiles of the respondents concerned. The angles between the vectors are a function of the relationships between the items they represent: angles close to 0 (180) degrees indicating strong positive (negative) relationships between items, and angles close to 90 and 270 ° indicating weak relationships between items. The coordinates of the points on the components are called object scores and can be used in further analyses as quantifications of the respondents on the latent variables represented by each component.

Bivariate analyses were used to investigate possible differences between the three age groups. When the dependent variable was numerical one-way analysis of variance (ANOVA) was used to test for differences; when the dependent variable was nominal a chi-square test was used instead.

Path analysis in AMOS (22.0) for SPSS was performed to investigate the multiple linear relationships between the variables in the path model shown in *Figure 4.1* (see the *Results* section for further details). In path analysis an observed variable may be simultaneously treated as an independent (exogenous) and a dependent (endogenous) variable. Specifically, in this study, a path analysis can be used to investigate the influence of listening to music and talking on the phone on cycling safety (startle reactions), while controlling for cyclists' characteristics, time spent cycling and characteristics of the traffic environment as important background variables. For each age group, the hypothetical path model was tested and a final model was developed using a cross-validation strategy. The dataset was randomly split into two subsets: a calibration sample and a validation sample. The calibration sample was used to test the hypothetical model as well as to conduct post-hoc

analyses to attain the best-fitting model. The best model was obtained by first removing all statistically non-significant parameters, followed by iteratively freeing parameters as indicated by the modification indices, in order from largest to smallest index value, and thus continuing until further modifications only marginally improved the model fit. Once the final model was determined, its validity was then tested based on the validation sample. Maximum likelihood estimation was used. Various fit indices were used to assess the fit of the model: chi-square, the goodness-of-fit index (GFI), the adjusted goodness-of-fit index (AGFI), the root mean square error of approximation (RMSEA). Conventional cut-off values that indicate a good model fit ($RMSEA < 0.09$, GFI and $AGFI > 0.90$) were used to guide model evaluation and selection (see e.g. Byrne, 2010; Hu & Bentler, 1995). Furthermore, a non-significant chi-square had to be obtained. The chi-square test measures the discrepancy between a hypothesized model and the data (Bagozzi & Heatherton, 1994). Significant values of the chi-square test indicate a strong divergence between the data and the fitted model.

4.3. Results

4.3.1. Reliability and internal consistency of measures

For most of the 24 risk behaviour items of the questionnaire high scores on the items indicated non-risky behaviour, except for four items for which high scores indicated very risky behaviour. Before analysing the risk behaviour items with a categorical principal component analysis (CATPCA), these four items were recoded in such a way that high scores also indicated non-risky behaviour. Using the eigenvalue- larger-than-one criterion (see e.g. Tabachnick & Fidell, 2007) a first two-dimensional solution with the CATPCA was found accounting for 55.1% of the variance in the data (the first component accounted for 49.6% and the second for 5.5% of the total variance). All items had high positive loadings on the first component except for the four recoded items consisting of one Error-item and three Lack of protective behaviour- items who all had high positive loadings on the second component. This suggests that the respondents were more sensitive to the reversed wording of these four items than to their actual content. A second ordinal CATPCA without the latter four items again yielded a two-dimensional solution, now accounting for 57.8% of the total variance in the data (with 51.7% on the first and 6.1% on the second component). Now all the remaining 20 items had higher (positive) loadings on the first than on the second component, see *Table 4.2*. Moreover, the loadings on the second component

did not discriminate between the Error-, the Violation- and the Lack of protective behaviour-items meaning that no confirmation was found for the hypothesized three-factor structure in the risk behaviour scale.

Table 4.2. Component loadings of the second CATPCA of 20 risk behaviour items (E = Error, V = Violation, L = protective behaviour).

	Dimension 1	Dimension 2
RB 1 (E)	0.802	-0.186
RB 2 (E)	0.699	0.325
RB 3 (L)	0.719	0.380
RB 4 (L)	0.810	-0.011
RB 6 (E)	0.745	0.112
RB 8 (E)	0.662	-0.273
RB 9 (V)	0.794	-0.189
RB 10 (V)	0.734	-0.118
RB 12 (V)	0.659	0.343
RB 13 (E)	0.731	-0.291
RB 14 (V)	0.804	-0.215
RB 15 (E)	0.748	-0.345
RB 16 (L)	0.589	0.364
RB 17 (L)	0.790	-0.092
RB 18 (V)	0.807	-0.207
RB 19 (V)	0.582	0.101
RB 20 (V)	0.637	0.392
RB 22 (L)	0.660	0.123
RB 23 (E)	0.649	-0.154
RB 24 (V)	0.689	0.212

The value of Cronbach's α for the 20 items in the second analysis is 0.94, whereas it is 0.88 for the full set of 24 items, confirming that the internal consistency of the 20 items is indeed better than that of the full risk behaviour scale. Since the first component of the second CATPCA could clearly be interpreted as a general risk behaviour component, the object scores of the respondents on this component were used as a latent risk behaviour variable in all further analyses, high scores being indicative of risky behaviour.

4.3.2. Respondent characteristics

The majority of the respondents reported good hearing (89.2% of cyclists aged 16–18 years: 84.6% of cyclists aged 30–40 years and 66.0% of cyclists aged 65–70 years). Most respondents (84.5%) usually cycled on a conventional bicycle (a ladies' bike or a men's bike). However, much more respondents (20%) in the oldest group usually cycled on an e-bike than the other age groups (2.7% of teenage and 0.5% of adult cyclists). The majority of the respondents cycled alone or more often alone than in company of other cyclists.

4.3.3. Time spent cycling and exposure to demanding situations

Teenagers spent significantly more time cycling ($M = 262$ min a week) than the adult ($M = 179$ min a week) and older respondents ($M = 240$ min a week): $F(2, 2248) = 8.25$; $p < 0.001$. The value of Cronbach's α for the 6 items measuring exposure to demanding situations is 0.84, indicating an internally consistent scale. Post-hoc tests with Bonferroni correction (see e.g. Kirk, 2012) applied to this scale revealed that teenagers and adult respondents cycled more often in demanding situations (respectively: $M = 3.35$, $SD = 0.70$ and $M = 3.30$, $SD = 0.75$) than the older cyclists ($M = 2.92$, $SD = 0.76$): $F(2, 2248) = 77.20$, $p < 0.001$.

4.3.4. Use of electronic devices

There were significant differences between age groups regarding frequency of listening to music ($\chi^2 = 847.4$; $df = 8$; $p < .001$), making a phone call ($\chi^2 = 459.8$; $df = 8$; $p < .001$), answering the phone ($\chi^2 = 409.8$; $df = 8$; $p < .001$), reading ($\chi^2 = 748.7$; $df = 8$; $p < .001$) and typing text messages ($\chi^2 = 734.3$; $df = 8$; $p < .001$), but no significant age differences were found concerning searching for information. Teenage respondents were the most frequent users of electronic devices while the oldest respondents rarely used electronic devices (see *Table 4.3*).

Listening to music while cycling was especially popular among teenage cyclists. It was reported by 77% of the teenage respondents, 43% of the adult respondents but only by 6.2% of the oldest respondents. Almost a quarter of the teenage cyclists reported listening to music on each trip. Listening to music was the most frequent device use among the teenagers while making a phone call was the least popular among this age group. Device use among adult cyclists is more homogeneous. About the same percentage of the adult respondents (40–45%) reported listening to music, making a phone call or texting while cycling. Searching for information was reported by about one-

third of the adult cyclists. Those who use devices do so rather infrequently. As far as the oldest group is concerned, only 6–10% of cyclists in this age group reported using devices while cycling. The older adults who use devices do so only rarely.

Table 4.3. Frequency of electronic device use per age group; the table shows usage percentages of the various devices listed in the columns, for each age group.

Age group	Frequency of use	Percentage of cyclists			
		Listening to music	Making a phone call	Texting: reading/typing	Information search
16-18	never	23.0	37.3	26.7/ 29.4	41.3
	seldom	14.2	36.8	21.4/ 21.8	28.9
	on some trips	19.5	20.6	29.3/ 27.4	18.2
	on most trips	19.1	2.9	14.4/ 13.9	7.5
	on all trips	24.2	2.4	8.2/ 7.5	4.1
30-40	never	57.5	57.0	55.3/ 59.8	68.1
	seldom	14.8	26.2	24.8/ 22.7	18.6
	on some trips	11.5	11.9	14.6/ 12.0	9.2
	on most trips	9.9	2.7	3.1/ 3.5	2.0
	on all trips	6.3	2.3	2.3/ 2.0	2.1
65-70	never	93.8	89.9	90.8/ 93.4	89.8
	seldom	4.3	8.6	7.2/ 5.3	7.6
	on some trips	1.3	1.2	1.5/ 0.9	2.1
	on most trips	0.3	0.1	0.1/ 0.1	0.3
	on all trips	0.4	0.1	0.4/ 0.3	0.3

The most popular manner of listening to music in each age group was using both earbuds (reported by about 40% of the respondents) followed by using one earbud (chosen by 21–23% of the respondents) (*Table 4.4*). The manner of listening to music differed significantly between age groups ($\chi^2 = 35.15$; $df = 12$; $p < .001$). For example, using in-earbuds was reported by about 16% of the teenage and the adult cyclists but by none of the older cyclists. There were also significant differences between age groups concerning the frequency of listening to music while cycling in demanding situations ($F(2,940) = 15.28$, $p = .00$). The older cyclists refrained most often ($M = 2.62$, $SD = 0.98$) and the teenage cyclists ($M = 1.91$, $SD = 0.98$) least often from listening to music while cycling in demanding situations, with the adult cyclists taking in a middle position ($M = 2.16$, $SD = 1.03$). All pairwise post-hoc tests were significant.

Table 4.4. Percentage of cyclists reporting specific manners of listening to music per age group.

	Age group		
	16-18	30-40	65-70
2 earbuds	40.6	38.7	40.4
1 earbud	22.6	22.3	21.3
2 in-earbuds	15.5	16.4	0
1 in-earbud	6.6	7.5	2.1
Headphone	4.5	5.7	4.3
Loudspeaker	3.8	5	8.5
Alternating	6.4	4.4	23.4
<i>Total</i>	<i>100</i>	<i>100</i>	<i>100</i>

4.3.5. Auditory perception

A great majority of the respondents, about 90% in each age group, indicated that a cyclist should hear all or most sounds in order to cycle safely (*Figure 4.2a*).

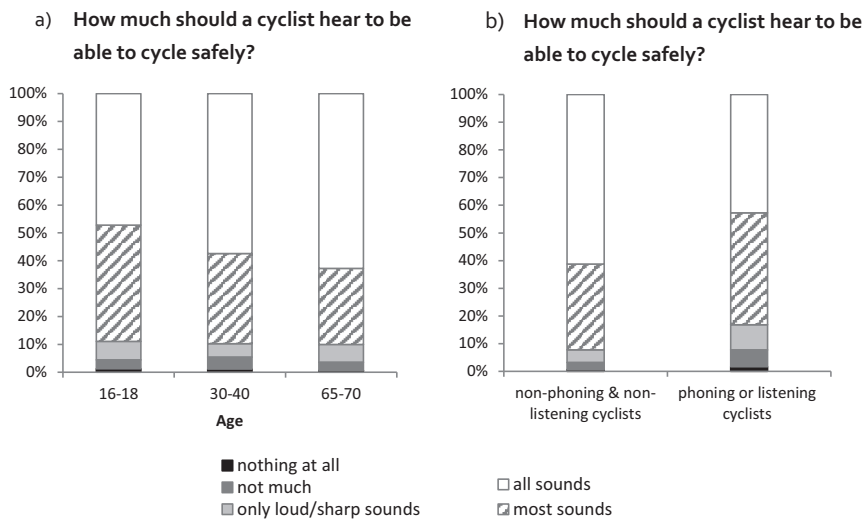


Figure 4.2. The extent to which cyclists should hear traffic sounds to be able to cycle safely per age group (a) and per type of cyclist (phoning/listening to music versus non-phoning/listening to music) (b).

A higher percentage of the older respondents (63%) than teenage (47%) or the adult respondents (57%) reported that cyclists should be able to hear all sounds. These age differences were significant: ($\chi^2 = 47.0$; $df = 8$; $p < .001$). Only 1% of the respondents in each age group indicated that a cyclist does not have to hear anything at all in order to be able to cycle safely.

Figure 4.3a shows that 66%-81% of the respondents report being able to hear all or most sounds while listening to music. The higher percentage corresponds to the oldest group, and the lower percentage to the adult cyclists (no test possible: chi-square test was invalid). With regard to talking on the phone, about three-quarter of the respondents in the two younger groups and two-thirds in the oldest group claim they can hear all or most sounds. Especially the teenagers reported being able to hear all sounds. The age differences found were significant: ($\chi^2 = 42.0$; $df = 10$; $p < .001$).

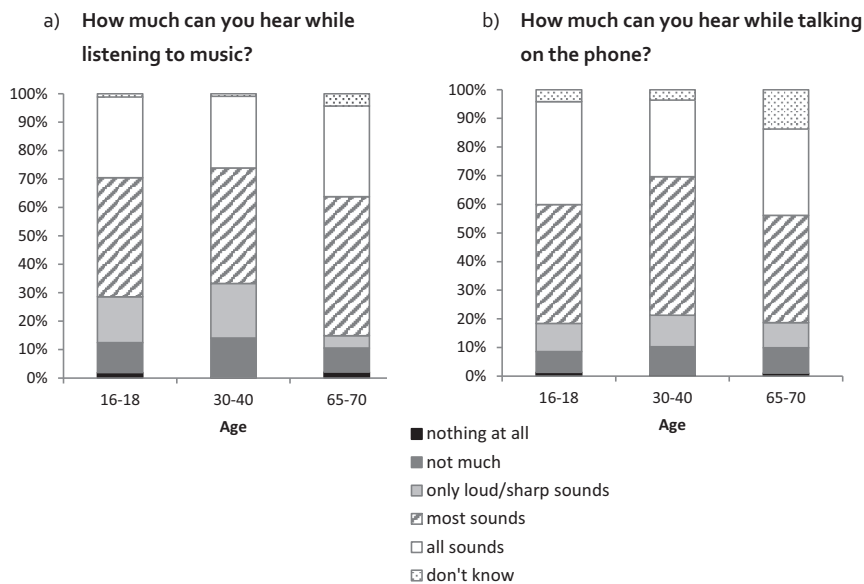


Figure 4.3. The extent to which cyclists can hear sounds when and listening to music (a) and talking on the phone (b) per age group.

When comparing Figures 4.2a with 4.3a and 4.3b, we can see that, according to the respondents a cyclist should hear more than what can be heard by the cyclists who listen to music or talk on the phone when cycling. Furthermore, when comparing the cyclists who listen to music and/ or talk on the phone with those who never engage in those activities, we can see that compared to

cyclists who listen to music and/or talk on the phone, a higher percentage of cyclists who never engage in those activities indicated that cyclists should hear all sounds in order to cycle safely ($\chi^2 = 78.6$; $df = 4$; $p < .001$) (Figure 4.2b).

Finally, there were also significant differences between the age groups with regard to the two questions about quiet (electric) cars. Between 19 and 33% of the respondents (19% of the older, 24% of the teenage and 33% of the adult respondents) encountered (quiet) electric cars at least regularly (Figure 4.4a). In comparison with the two other age groups, a higher percentage of the older cyclists reported that they never encounter quiet (electric) car when cycling ($\chi^2 = 58.2$; $df = 10$; $p < .001$). About 47–32% reported not knowing how an electric car sounds like (see Figure 4.4b) ($\chi^2 = 34.0$; $df = 10$; $p < .001$).

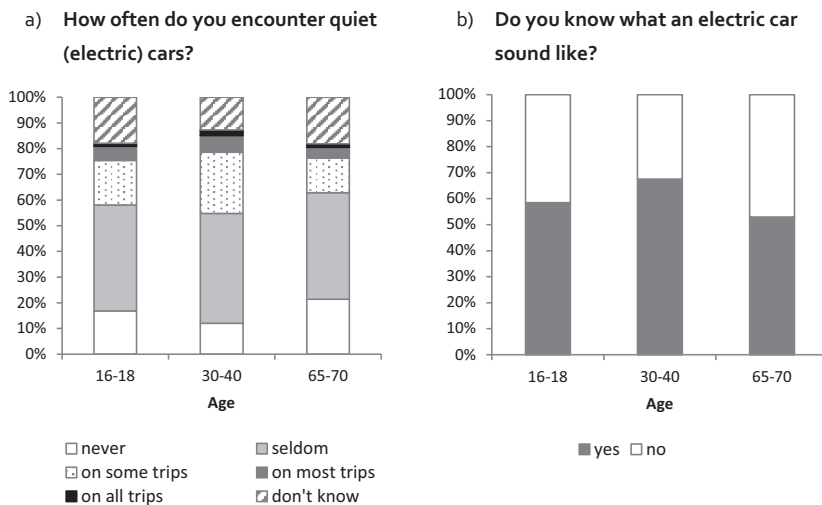


Figure 4.4. Cyclists' experiences with electric vehicles: a) frequency of encountering of quiet (electric cars and b) knowing what an electric car sound like per age group.

4.3.6. Compensatory behaviour

In comparison with adult and older cyclists, a lower percentage of teenage cyclists reported adapting their behaviour to compensate for listening to music or talking on the phone. Compensatory behaviour for listening to music was reported by 65% of the teenage cyclist, 72% of the adult cyclists and 70% of the older cyclists (but these differences are not significant). The most often chosen types of compensatory behaviours for music were: looking around more

frequently, turning the music down or off if it is necessary and using one earbud instead of two. The majority of the respondents (64% of the teenage, 76% of the adult and 85% of the older cyclists, these age differences being significant: $\chi^2 = 20.5$; $df = 2$; $p < .001$) reported refraining from listening to music in some specific traffic conditions, especially in bad weather, heavy traffic and complex traffic situations.

Compensatory behaviour for talking on the phone was reported by 67.4% of the teenage, 78% of the adult and 79% of the older cyclists (but these differences are not significant). The most often reported types of compensatory behaviour for having a phone call while cycling were: generally decreasing cycle speed and keeping the phone call short. Furthermore, the teenage and the adult cyclists often reported looking around more frequently and cycling more slowly when approaching a complex traffic situation as a compensatory strategy. The majority of the respondents (77% of the teenage, 84% of the adult and 82% of the older cyclists, these age differences being significant: $\chi^2 = 12.5$; $df = 2$; $p < .01$) reported refraining from listening to music in some specific traffic conditions, again especially in bad weather, heavy traffic and complex traffic situations.

4.3.7. Sensation seeking

The value of Cronbach's α for the 19 items of the sensation seeking scale is 0.83, indicating an internally consistent scale. Significant age differences were found for this scale: $F(2, 2248) = 128.73$; $p < .001$. Teenage cyclists scored average (percentage true answers: 43%), adult cyclists scored low (40%) and older adults very low on this personality trait (26.7%).

4.3.8. Risk perception

The value of Cronbach's α for the 4 items of the risk perception scale is 0.91, again indicating an internally consistent scale. Respondents scored relatively low on the risk perception scale: $M = 2.4$ for the teenage cyclists, $M = 2.6$ for the adult respondents and $M = 2.7$ for the older respondents, the response options ranging from 1 = low risk perception to 6 = high risk perception. These age differences in risk perception were significant: $F(2, 2248) = 14.77$; $p < .001$.

4.3.9. Risky cycling behaviour

We found significant differences between the object scores of the three age groups on the general risky behaviour component obtained from the CATPCA (see Section 4.3.1): $M = -0.364$ for the teenage respondents; $M = -0.065$ for the

adult respondents and $M = 0.426$ for the older respondents ($F(2,2246) = 133.37$, $p < 0.001$). Since high scores correspond with non-risky behaviour, the older age group displays the safest behaviour on average.

4.3.10. Incidents

Significant differences in the frequency of getting startled or surprised by some other road user in the past month were found also between age groups ($\chi^2 = 54.1$; $df = 6$; $p < .001$) (Figure 4.5a). More than half of the respondents in each group had never got startled or surprised in the past month (52% of teenage, 58% of the adult and 56% of the older cyclists). A higher percentage of the older respondents got startled/surprised 'more than once' as compared to the teenage or adult respondents.

The teenage and adult respondents got startled or surprised especially by car drivers and cyclists. The older respondents got also often startled or surprised by (light) moped riders ($\chi^2 = 70.2$; $df = 10$; $p < .001$) (Figure 4.5b). Not hearing another road user was reported as a cause of the incident by 28% of the adult, 30% of the teenage and 39% of the older cyclists. The age differences were significant, ($\chi^2 = 8.96$; $df = 2$; $p < .05$).

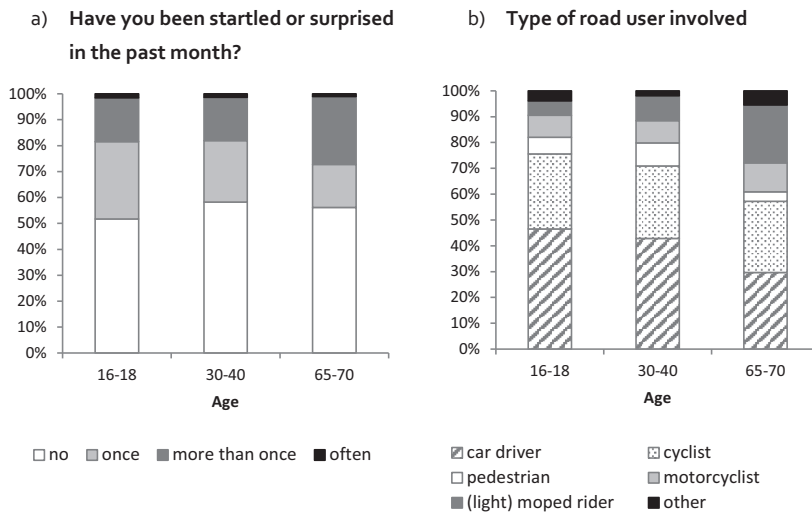


Figure 4.5. Startle/surprised reactions in the past month: (a) frequency of music and talking on the phone and (b) other road users involved.

4.3.11. Crashes

Crash involvement in the past 12 months was reported by 8% of the teenage cyclists; 4.9% of the adult cyclists and 5.1% of the older cyclists (see *Table 4.5*). As respondents who were involved in more than one crash were asked to provide further details about the most recent crash, the total number of crashes ($N = 180$) is higher than the number of crashes with known details ($N = 138$). As a result the details about 42 crashes are not known.

Details regarding specific circumstances preceding or accompanying the crash are summarized in *Table 4.6*. As we can see many crashes took place when the cyclist was 'just' cycling. The most often reported circumstance preceding or accompanying the crash was poor visibility.

Table 4.5. Reported crashes per age group.

Nr of crashes	Age group															Total nr of crashes			
	16-18					30-40					65-70								
	1	2	3	4	5	1	2	3	4	Total	1	2	3	4	Total				
Frequency	52	5	2	1	2	82	27	7	2	1	51	33	5	0	1	47	180		
Nr of crashes with known details*						62						37						39	138

*When more than one crash was reported by a respondent, details were asked about the most recent crash.

Crashes in which limited auditory perception, marked grey in *Table 4.6*, might have played a role constitute 13% of all crashes with known detail. Surprisingly, none of the older respondents reported getting involved in these crashes. Quietness of other road users may have played a role in 5% of the crashes reported by the teenage cyclists and 2% of the crashes reported by the adult cyclists. Environmental noise was present in 5% of crashes reported by the teenage and the middle aged cyclists. Two percent of bicycle crashes reported by the teenage and by the adult cyclists was related to talking on the phone. Finally, listening to music was associated with 6% of the crashes reported by the teenagers and 9% of the crashes reported by the adult cyclists.

We can also notice that the older respondents differ strongly from the two younger groups. A great majority of the older respondents was 'just cycling' when the crash took place. The remaining crashes were related to being busy or distracted by factors other than those specifically mentioned in *Table 4.6*.

The results concerning various circumstances preceding or accompanying crashes should, however, be treated with caution due to the small number of crashes reported by our respondents.

Table 4.6. Specific circumstances preceding or accompanying the crash per age group.

Circumstance	% of crashes		
	16-18	30-40	65-70
Just cycling	42	50	89
Poor visibility	17	11	0
Much environmental noise	5	5	0
Road user involved was very quiet	5	2	0
Talking on the phone	2	2	0
Talking to a fellow cyclist	9	7	0
Listening to music	6	9	0
Texting	0	7	0
Searching for information	5	5	0
Busy/ distracted by something else	9	2	11
Total	100%	100%	100%

4.3.12. Impact of listening to music and talking on the phone on crashes and noise-related incidents.

As mentioned in *Section 4.3.11* just over 6% of the respondents reported having been involved in a bicycle crash. This low percentage did not allow for further statistical analysis. Therefore, the frequency of getting startled or surprised ('Incidents') was chosen as an alternative indicator of cycling safety in the AMOS path analysis. Getting startled or surprised by another road user is a potentially dangerous situation as it implies a cyclist's failure to perceive the other road user or to understand their current behaviour in time. This failure can be linked to low situation awareness, unjustified expectations and poor hazard anticipation (e.g. Kinnear et al., 2013) – concepts which have shown to be important for traffic safety. As the data were non-normally distributed, maximum-likelihood (ML) estimation in AMOS was used with bootstrapping (1000 boot- straps were performed). When the hypothesized model shown in *Figure 4.1* was tested on the calibration sample, this resulted in an insufficient fit for all age groups. For the older age group, re-specification and re-estimation of the model in the post-hoc analysis did not result in an improvement of the model fit. For the adult group, post-hoc model fitting resulted in a model that met the goodness-of-fit criteria. This model did not,

however, fit the validation set. The cross-validation procedure was only successful for the youngest group. The final model obtained with the calibration data also fitted the validation data. We therefore only present the results of the path analysis for the teenage cyclists. *Table 4.7* presents the goodness-of-fit indices for the final solution for the calibration and the validation sample for this age group.

Table 4.7. Goodness-of-fit indices of the model for the calibration ($N=374$) and validation ($N=374$) and the whole sample for teenage cyclists ($N=748$).

	$\chi^2(df)$	GFI	AGFI	RMSEA	<i>p</i> -close	<i>p</i> -value
Calibration sample	2.77(5)	.998	.988	.000	.94	.735
Validation sample	10.87(5)	.992	.954	.056	.35	.054
Whole sample	10.347(5)	.996	.978	.038	.69	.066

Figure 4.6 shows the final model for the complete sample of teenage cyclists. Cycling exposure was not related to any other endogenous variable and was therefore removed from the model. The variables *Complex situations*, *Sensation seeking* and *Risk perception* explained 23% of the total variance in *Phone conversation*, 12% of the total variance in *Listening to music* and 10% of the total variance in *Risky behaviour* (risky behaviour other than listening to music or talking on the phone). As indicated by the size of the standardised path coefficients (values above the arrows) most effects in the model are rather small, except for a medium effect of sensation seeking on *Risky behaviour* (0.29). *Sensation seeking* is related to listening to music, *Phone conversation* and *Risky cycling behaviour*. Thus the higher the respondents' scores on sensation seeking, the more frequent they listen to music, talk on the phone and engage in risky behaviour while cycling. There was a small positive effect of the frequency of cycling in complex situations on the frequency of listening to music and talking on the phone.

However, the frequency of cycling in complex situations was not related to risky cycling behaviour. *Risk perception* was negatively related to *Listening to music* suggesting that individuals with a higher risk perception listen to music less often than those with a low risk perception. There was, on the other hand, a positive relationship between *Risk perception* and *Risky cycling behaviour* indicating that the higher risk perception of cyclists was, the more frequently cyclists engaged in risky cycling behaviour. *Figure 4.6* shows also that there is

a positive relationship between *Phone conversation* and *Listening to music*. These two activities were also related to other *Risky cycling behaviour*.

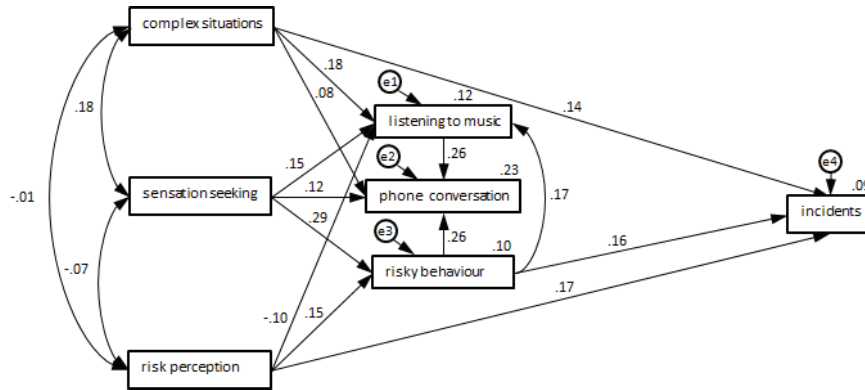


Figure 4.6. The final model; e1 to e4 represent error terms (residual variances within variables not accounted for by pathways hypothesized in the model).

Finally, we can see that 9% of the total variance in ‘Incidents’ is explained by a direct effect (0.14) of *Complex situation* as well as by both an indirect very small effect mediated via *Risky behaviour* ($0.15 * 0.16 = 0.02$) and a direct effect (0.17) of *Risk perception*. The frequency of cycling in demanding situations was related to the frequency of getting startled or surprised in traffic, but listening to music and talking on the phone were not.

4.4. Discussion

The use of auditory cues has become more challenging for cyclists due to listening to music or conversing on the phone while cycling but also due to the quietness of slow-moving electric cars. Given the widespread use of mobile phones, and more recently smartphones by younger cyclists, and ambitious deployment targets for electric cars in many countries, it is increasingly important to examine the relationship between limited auditory information and cycling safety. To achieve a better understanding of this relationship, the present study examined auditory perception, compensatory behaviour and involvement in crashes and incidents among cyclists in three age groups.

4.4.1. Age differences

The greatest age differences were generally found between the oldest respondents and the other two age groups. The differences between teenagers and adult respondents were often less pronounced. In line with previous studies, we found that both listening to music and talking on the phone are much more popular among teenage cyclists than among older age groups. Only a small percentage of cyclists in the oldest age group reported that they (rarely) engaged in these activities. Although older cyclists generally seldom listen to music or talk on the phone, a higher percentage of them reported getting startled or surprised more than once by other road users compared to the two younger age groups. A decline in hearing acuity with advancing age (e.g. Schieber & Baldwin, 1996), also observed in our sample, could explain this finding. Older cyclists may have had problems with auditory detection and localisation of other road users. Previous research found that the elderly are less accurate at auditory detection and localisation of moving cars than younger adults (Mendonça et al., 2013; Stelling-Kończak et al., 2016). It is important that future studies address the issue of older cyclists' not being able to hear other road users. Furthermore, a higher percentage of older cyclists reported getting surprised or startled by a (light) moped rider compared to teenage and adult cyclists. Possibly, these differences may originate from speed differences between older cyclists and (light) moped riders. (Light) moped riders ride on average faster than cyclists (Schepers, 2010); and older cyclists cycle on average at lower speeds than younger cyclists (Schleinitz et al., 2017; Vlakveld et al., 2015). As a result light moped riders possibly overtake older cyclists more frequently and with a higher speed difference causing older cyclists, who generally have poorer hearing, to startle more often than younger cyclists. Except for hearing problems, other functional limitations which accompany ageing, such as declines in visual functions, fluid intelligence, speed of processing, working memory and motor functions (see e.g. Davidse, 2007), may also explain the age differences found in this study. Research shows that older cyclists experience difficulties at the operational level (indicating direction with the left hand and looking over the shoulder). Older cyclists were also found to have lower grip strength scores, a higher mental workload and longer reaction times while cycling and to perform more corrections to stabilize a bicycle than middle-aged cyclists (Kováčsová et al., 2016; Vlakveld et al., 2015). These functional limitations do not necessarily have to lead to unsafe traffic situations, since older road users can consciously or unconsciously compensate for the limitations. Older drivers, for example, often choose to drive during daytime and dry weather (Smiley, 2004). There

are various factors which may facilitate compensatory behaviour among older road users: they have more freedom to choose when to travel, they generally have more experience in traffic (which can help them to anticipate possible hazards) and the desire for sensation and excitement decreases with age (older road users are for example more inclined to obey the rules). Little is known about compensatory behaviour of older cyclists. However, it has been argued that the ability of older road users to compensate is possible only up to a certain point at which the functional limitations begin to outweigh the advantages related to experience and cautious behaviour. As a consequence of not being able to fully compensate for their functional limitations, paired with the age-related increase in physical fragility, the crash risk of older road users begins to increase (see also Davidse, 2007; Holland, 2001).

4.4.2. Auditory perception of cyclists

The present study shows also that listening to music and talking on the phone negatively affect the perception of sounds crucial for safe cycling. Cyclists reported that they could hear less sound when listening to music or talking on the phone than is necessary for safe cycling. Listening to music was found to have more impact on auditory perception than talking on the phone. Our findings confirm the results of a previous field study showing that cyclists more often miss important auditory information when listening to music than when talking on the phone (De Waard, Edlinger & Brookhuis, 2011). In the introduction we provided two potential explanations for the negative effects of music and telephone conversation on auditory perception: auditory masking and distraction. A recent fundamental study into auditory localisation of critical environmental sounds suggests that the negative effects of music and telephone conversation could be attributed to masking effects rather than to the effects of distraction (May & Walker, 2017). May and Walker have found that auditory localisation was not affected by whether listeners ignored or attended to distractors. Furthermore listening to music with lyrics was more detrimental than speech for auditory localisation of across almost all sounds (including the broad- band white and pink noise); this is probably due to the greater range of frequencies of the masking sound present in music with lyrics. Auditory information can act as an attentional trigger and can facilitate detection and localisation of other road users. Not being able to hear relevant traffic sounds can have serious consequences for cyclists, especially in situations where cyclists rely on auditory information, e.g. due to visibility obstruction or visual distraction. If the limited auditory input is not

compensated for by, for example, the increase in visual attention, the safety of cyclists is likely to be compromised.

4.4.3. Compensatory behaviour while listening to music and talking on the phone

In line with previous studies using self-reported data, the majority of cyclists who listen to music or talk on the phone were found to use compensatory strategies. Compensatory behaviour was reported by about two-thirds of the teenage respondents in the present study. The most often mentioned compensatory strategy for listening to music was turning the music down or off when necessary, looking around more frequently or using one earbud instead of two. Decreasing speed, keeping conversations short and looking around were the most often reported compensatory strategies for talking on the phone. The results are in line with the Internet survey by Goldenbeld et al. (2012) and partly in line with the recent findings of the studies in real traffic (Ahlstrom et al., 2016; Kircher et al., 2015). Reducing speed has generally positive effects on traffic safety. However, too low speeds can pose a safety risk (lower than about 14 km/h) requiring the cyclist to put more effort in stabilizing the bicycle (see e.g. Schwab, Meijaard & Kooijman, 2012), and causing decrements in lateral control. In contrast to texting, listening to music and talking on the phone has neither been found to affect cyclists' average lateral position nor the variation in lateral position (De Waard et al., 2010).

The findings concerning visual behaviour of cyclists found in our study and other surveys appear inconsistent with the results of on-road studies. Specifically, the increase in visual behaviour reported by cyclists in survey studies is not found in on-road research in which cyclists' visual behaviour whilst listening to music was similar to the visual behaviour while 'just' cycling (Ahlstrom et al., 2016; Stelling-Kończak et al., 2018). As for talking on the phone, cyclists who engaged in this activity were in the study of Ahlstrom et al. found to use visual strategies: they decreased their glances towards traffic-irrelevant targets and shortened glance durations to traffic relevant targets, while maintaining the number of glances. The inconsistency concerning compensatory behaviour between the results of surveys and on-road studies could also be due to the difference in the studied traffic environment. Contrary to the field studies, the surveys did not concern specific, relatively undemanding traffic environments, leaving open the possibility that cyclists who listen to music or talk on the phone do increase their visual attention only in some, for example more demanding, traffic situations. Finally, surveys generally rely on what people think they do rather

than their actual behaviour. Road users, and human beings in general, tend to overestimate their (driving) skills (see e.g. De Craen et al., 2011; Taylor & Brown, 1988). This phenomenon has recently also been found in a study among cyclists (Kováčsová et al., 2016).

4.4.4. Involvement in crashes and incidents

Finally the present study investigated the extent to which listening to music and talking on the phone impact the safety of cyclists. As crashes are rare events, incidents were used as an alternative indicator of cycling safety. Taking into account the influence of confounding variables, no relationship was found between the frequency of listening to music or talking on the phone and the frequency of incidents among teenage cyclists. This may be due to cyclists' compensating for the use of portable devices, as mentioned before. Another explanation for the lack of the relationship between listening to music or talking on the phone and incidents might be behavioural adaptation of other road users who encounter a cyclist using electronic devices. Car drivers might, for example, adapt their behaviour to compensate for the possible dangerous behaviour of the cyclist, e.g. they may drive more carefully knowing that more and more cyclists are using various electronic devices (for examples of behavioural adaptation in traffic see Rudin-Brown & Jamson, 2013). This explanation seems less probable since it may not be easy for car drivers to detect whether a cyclist is using electronic devices. Our results show for example that only about 5% of cyclists who listen to music use headphones – the majority of cyclists use one or both earbuds which are hardly visible from a distance. Furthermore, although both listening to music and talking on the phone have been found to affect cycling behaviour, the changes in cycling behaviour may not be directly observable for car drivers. Specifically, talking on the phone while cycling has been related to a decrease in speed and an increase in reaction time as well as in the number of unsafe behaviours. Cyclists who listen to music have also been observed to engage in unsafe behaviours. Additionally, these cyclists have been found to disobey traffic rules more frequently than those who 'just' cycle (see Stelling-Kończak, Hagenzieker & Van Wee, 2015). The present study also found that cyclists in all age groups got startled or surprised mainly by car drivers and other cyclists. This finding may not be surprising as these are the road users that cyclists in the Netherlands are most likely to encounter. On the other hand, cyclists are 'silent' road users who can presumably be more easily missed than 'noisy' cars.

Finally, the frequency of getting involved in an incident was found to be positively related to cycling in complex situations, risk perception and risk cycling behaviour. Listening to music and talking on the phone was not related to incidents but it was positively related to other risk cycling behaviour. These findings underline the importance of taking into account the influence of confounding variables, such as cycling in complex traffic situations and other risk behaviour when estimating the impact of secondary tasks on cycling safety. Listening to music and talking on the phone apparently co-occur with other risk behaviour.

4.4.5. Implications

Although the results of this study show that listening to music or talking on the phone does not impact cycling safety measured by incidents, we cannot conclude that engaging in these activities whilst cycling is without risk. The effect of performing such secondary tasks on cycling safety is likely to depend on the traffic environment and on the cyclist's compensatory strategies (see the model in *Figure 4.1*). Listening to music or talking on the phone while cycling may still pose a safety threat in the absence of compensatory behaviour or a traffic environment with less extensive and less safe cycling infrastructure than the Dutch setting.

Given the popularity of listening to music among teenage cyclists, we may need countermeasures that discourage listening to music whilst cycling. Some countries (Germany, New Zealand, a few states in the USA) have already banned cyclists from wearing headphones while on the road. In the Netherlands, as well as many other countries, it is not forbidden for cyclists to listen to music. However, by reason of a general law in these countries listening to music while cycling can be fined if it results in hazardous behaviour (Meesmann, Boets & Tant, 2009). Education and public information can raise cyclists' awareness of the dangers associated with listening to music while on the road. Recently, specifying implementation intentions ("if-then" plans) have been found effective in encouraging safer driving behaviour, i.e. speeding behaviour (see Brewster, Elliott & Kelly, 2015). This new type of intervention may also have the potential to break the habit of listening to music while cycling. Other solutions seem promising in mitigation of the negative effects of listening to music while cycling. Listening to music at low volume, using one earphone instead of two or using music devices with a built-in microphone allowing for simultaneous music and surrounding sounds playback may allow cyclists to utilize auditory cues from the traffic

environment. However, further research into the safety effects of these solutions is needed before they can be recommended.

The rising number of electric cars may also have impact on the safety of cyclists in general and those who listen to music or talk on the phone. Many countries, including the Netherlands, aim at increasing the number of those cars considerably. The majority of the cyclists in this study indicated that they never or seldom encountered quiet (electric) cars when cycling. This is in line with Dutch statistics showing that only about 2% of the total number of cars in the Netherlands is electric or hybrid¹⁷ With the increasing number of quiet (electric or hybrid) cars, cyclists in general and those who listen to music and talk on the phone will encounter electric cars more frequently in the future. The frequency of incidents caused by failing to hear these cars may increase, especially during transition periods where cyclists will have to cope with a mix of vehicles having various acoustic properties.

4.4.6. Limitations

One of the limitations of this study is the use of subjective assessments, which can have important disadvantages (social desirability, possible non-accurate recall, or selective non-response bias). Care was taken to limit these disadvantages. Our Internet survey guaranteed anonymity and the topic of the survey was quite neutral: listening to music and talking on the phone are not illegal in the Netherlands, which may encourage respondents to be honest in their answers. To enhance accurate recall, cyclists were asked to report recent incidents – incidents taking place in the past month. Cyclists spent a few hours a week on cycling, thus the topic of the survey concerned a familiar activity. Pre-testing confirmed that the questionnaire was clear and readable. However, some bias cannot be excluded. Most traffic behaviours are automatic and therefore not consciously monitored. They may not be easily recalled. Cyclists may for example not be consciously aware of specific encounters with electric cars or of what they can and cannot hear while cycling. Another limitation regards the correlational design of the present study, since correlation does not imply causation. Generally causal effects cannot be proven unless variables have experimentally been manipulated.

¹⁷ At the time of data collection (in 2014) 1.7% of the total number of cars in the Netherlands was electric or hybrid; currently (2016) 2.6% of cars are electric or hybrid (BOVAG/RAI, 2016).

4.4.7. Concluding Remarks

In this study both listening to music and talking on the phone was found to diminish cyclists' auditory perception. However, engaging in these activities was not found to negatively impact cyclists' involvement in incidents. This could be due to the use of compensatory strategies by cyclists. The majority of cyclists who reported listening to music or talking on the phone also reported using compensatory strategies. Listening to music or talking on the phone without compensatory strategies may still pose a safety threat. This study shows furthermore that the majority of the cyclists never or seldom encountered quiet (electric) cars on the road. However, as the number of electric and hybrid cars is increasing, the question arises whether cyclists in general – and those who listen to music or to talk on the phone in particular – will sufficiently compensate for the limited auditory input of these cars in the future.

5. Glance behaviour of teenage cyclists when listening to music ¹⁸

The previous chapter showed that teenage cyclists' listening to music does not increase a risk of getting involved in a self-reported incident. One explanation of this finding was cyclists' use of adaptive strategies to compensate for the restricted auditory perception. Indeed, as shown in the previous chapter, two-thirds of teenage cyclists reported using adaptive strategies to compensate for listening to music, e.g. increasing their visual attention. However, this self-reported data could not provide quantitative evidence on the location and duration of one's visual effort. Therefore, in *Chapter 5*, eye movements of teenage cyclists are measured in the real traffic. The study has three aims: 1) to explore whether and to what extent teenage cyclists' glance behaviour is affected by listening to music, 2) to demonstrate ethical dilemmas related to performing research in real traffic and 3) to examine the suitability of the applied experimental set-up.

Section 5.1 presents background information including previous research into cyclists' glance behaviour. It also discusses the importance of taking ethical considerations into account to protect participants taking part in an on-road study. At the end of this section the rationale for the study is provided. *Section 5.2* presents the methods used to address the three study aims. An eye-tracker was used to measure cyclists' glance behaviour during two of their regular trips: during one trip cyclists were listening to music, during the other one they were 'just' cycling. The study focuses on glances at uncontrolled intersections and takes a number of ethical considerations into account. *Section 5.3* reports the results regarding the glance behaviour for the two trip types and the evaluation of the experimental set-up. It also explains why the experiment was stopped. Next, *Section 5.4* discusses the results and provides major conclusions.

¹⁸ This chapter was first published in Transportation Research Part F: Traffic Psychology and Behaviour: Stelling-Konczak, A., Vlakveld, W.P., Van Gent, P., Commandeur, J.J.F., Van Wee, G.P., Hagenzieker, M., (2018). *A study in real traffic examining glance behaviour of teenage cyclists when listening to music: Results and ethical considerations*. Transportation Research Part F: Traffic Psychology and Behaviour, vol. 55, p. 47-57.

ABSTRACT Listening to music while cycling impairs cyclists' auditory perception and may decrease their awareness of approaching vehicles. If the impaired auditory perception is not compensated by the cyclist himself or other road users involved, crashes may occur. The first aim of this study was to investigate in real traffic whether teenage cyclists (aged 16–18) compensate for listening to music by increasing their visual performance. Research in real traffic may pose a risk for participants. Although no standard ethical codes exist for road safety research, we took a number of ethical considerations into account to protect participants. Our second aim was to present this study as a case study demonstrating ethical dilemmas related to performing research in real traffic. The third aim was to examine to what extent the applied experimental set-up is suitable to examine bicyclists' visual behaviour in situations crucial for their safety. Semi-naturalistic data was gathered. Participants' eye movements were recorded by a head-mounted eye-tracker during two of their regular trips in urban environments. During one of the trips, cyclists were listening to music (music condition); during the other trip they were 'just' cycling (the baseline condition). As for cyclists' visual behaviour, overall results show that it was not affected by listening to music. Descriptive statistics showed that 21–36% of participants increased their visual performance in the music condition, while 43–64% decreased their visual performance while listening to music. Due to ethical considerations, the study was therefore terminated after fourteen cyclists had participated. Potential implications of these results for cycling safety and cycling safety research are discussed. The methodology used in this study did not allow us to investigate cyclists' behaviour in demanding traffic environment. However, for now, no other research method seems suitable to address this research gap.

5.1. Introduction

Listening to music is popular among cyclists in, for example, the Netherlands and Sweden, especially among youngsters. In Dutch surveys listening to music was reported by about three quarters of adolescent cyclists (Goldenbeld et al., 2012; Schroer, 2014; Stelling-Kończak, Hagenzieker & Van Wee, 2014), 42% of young adults and only 6% of the elderly (65 years or older) (Stelling-Kończak, Hagenzieker & Van Wee, 2014). Both in Sweden and in the Netherlands, listening to music was found to be the most common technology-related activity among cyclists (Adell, Nilsson & Kircher, 2014; Stelling-Kończak, Hagenzieker & Van Wee, 2014). Research shows that listening to music negatively affects cycling behaviour. Observational studies found that cyclists listening to music disobeyed traffic rules more often (De Waard et al., 2010) and engaged in unsafe behaviours more frequently than those not performing a secondary task (Terzano, 2013). Furthermore, the results of a field experiment show that cyclists' auditory perception deteriorated when they were listening to music. Even moderate volume or moderate tempo music compromised cyclists' perception of bicycle bells: more than 60% of cyclists listening to music did not hear the bells. Loud music, high tempo music, and particularly music listened through in-earphones impaired even hearing of

loud sounds (i.e. horn honking). Cyclists' auditory perception was not affected only when music was listened to through one earphone. Finally, cyclists rated listening to music while cycling as more risky than "just" cycling. The higher the risk perception, the lower the frequency of listening to music (De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2010).

Two potential explanations can be found for these negative effects. Music, especially loud music, can mask traffic sounds. Quieter sounds are generally masked by louder sounds. The higher the sound intensity of the masking sound (e.g. music), the higher the intensity level of the masked sound (e.g. traffic sounds) must be before it can be detected (see e.g. White & White, 2014). Masking is, furthermore, more likely to occur when music contains similar frequency ranges as traffic sounds (White & White, 2014). Music can also distract attention from the environment toward inward experiences (thoughts, memories, emotions, moods) (see for example Herbert, 2013). Fundamental research found a reduction in eye movement activity (longer fixations, fewer saccades and more blinks) while listening to music, suggesting a decrease in vigilance under the influence of music (Schäfer & Fachner, 2015).

There are, however, some indications that cyclists compensate for listening to music by adapting their behaviour. In a Dutch survey two-thirds of teenage cyclists reported using adaptive strategies to compensate for listening to music (Stelling-Kończak, Hagenzieker & Van Wee, 2014). Increasing visual attention was found the most often reported type of compensatory strategy among Swedish and Dutch adolescents (Adell, Nilsson & Kircher, 2014; Stelling-Kończak, Hagenzieker & Van Wee, 2014). However, a Swedish field experiment where an eye-tracker was used, found no change in visual behaviour among cyclists who were listening to music (Ahlstrom et al., 2016). Similarly, Dutch field experiments showed that a number of objects (printed traffic signs and a clock) noticed by cyclists was not influenced by listening to music (De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2014). However, in these two latter studies visual behaviour was not directly measured. Instead, after each trip, cyclists were to report noticing the objects. Since the reporting took place after the trip, failure to mention the objects may have reflected cyclists' memory deficits instead of deficits in visual perception. Furthermore, the objects used in the studies were irrelevant for the traffic task.

The discrepancies between the findings from surveys and research performed in real traffic may be a result of the different methodologies employed and reflect the difference between what cyclists think they do and their actual visual behaviour. In the Dutch survey cyclists were asked to provide information about what they typically do while cycling with music. Furthermore, surveys rely on accuracy of memory and honesty of reporting and may reflect what people think they do, rather than their actual visual behaviour. In the field experiment of Ahlstrom, the actual visual behaviour in one specific traffic environment was monitored with an eye-tracker. The traffic environment studied consisted of a combined sidewalk/- cycle track alongside an urban street and physically separated from the street. The cycle track intersected four side roads to the right, where the track had priority over the side roads. The route was situated in a semi-industrial area where traffic densities were low to moderate. It can therefore be concluded that the traffic environment in the Swedish field experiment was relatively undemanding for cyclists. The results of the study leave open the possibility that cyclists who listen to music adapt their visual behaviour only in some situations, e.g. more demanding traffic situations. Therefore, the authors recommended performing a similar study in other traffic environments. Compared to self-reported data, monitoring cyclists' behaviour in real traffic by means of an eye-tracker is better able to provide quantitative evidence on the location and duration of one's visual effort. However, studies in real traffic can be problematic from an ethical point of view.

5.1.1. Ethical considerations

Research in real traffic generates important ethical issues as it can lead to increased risks for cyclists. Cyclists are vulnerable road users: contrary to car occupants, cyclists are unprotected by an outside shield. Cyclists have also a higher risk of injury or death¹⁹ than car occupants (ITF, 2013). Furthermore, as research has shown that listening to music is potentially risky for cyclists, those who engage in this activity may be at a higher risk than cyclists who 'just' cycle. Even if cyclists themselves accept risks in real traffic and decide to listen to music while on the road, it does not directly justify the researchers to inflict the same level risks on participating cyclists (see Svensson & Hansson, 2007).

¹⁹ Risk of injury or death = number of injured cyclists respectively cyclist deaths per distance travelled.

Therefore, it is of primary importance that researchers protect cyclists participating in an on-road study. This requires researchers to minimize the risks and to continually monitor the ongoing research for safety threats. If harmful results manifest, researchers should be prepared to terminate the study (see Svensson & Hannson, 2007). The need to interrupt a study, although desirable from the ethical point of view, may however threaten researchers' goal to conduct a 'publishable' research with statistically significant results. Statistically significant results are generally treated as more important than non-significant ones in many research fields: journal editors and reviewers tend to reject studies with non-significant results (Fanelli, 2011). This publication bias has a number of consequences, e.g. impoverishment of research creativity, favouring predictable results at the expense of pioneering, high-risk studies, increased prevalence of research bias and misconduct or over-interpretation of results (see e.g. Fanelli, 2011). In addition, non-significant results should be published so that other researchers do not waste their time and money for unnecessary repetition. As the likelihood of obtaining significant findings is also related to sample size, researchers often feel encouraged to recruit enough participants to get a sufficient statistical power in order to detect an effect if there actually is one.

Ethical approval is generally not mandatory for traffic safety research. To the best of our knowledge at the time of writing of this paper (January 2018) scientific journals for transport safety do not require a submission including human participants to be ethically approved. According to Svensson and Hannson (2007), only a part of road safety research is subjected to ethical supervision. A large part of road safety research, especially research performed outside universities, is carried out without the approval of ethics committees. In contrast universities nowadays tend to require ethical review for the approval of research. However, various ethical committees do not always reach the same conclusions, as shown for medical research (Edwards, Stone & Swift, 2007). Anecdotal evidence for inconsistencies in ethical review between various ethics committees is also known in the field of road safety research. To promote equal opportunities for researchers who aim to conduct an empirical study and to minimize risks which may arise when people participate in research, ethical codes for traffic research need to be created. According to Svensson and Hannson ethical codes which have already been developed for other fields of empirical research (e.g. biomedicine and psychology) can be useful for application in the field of traffic research.

5.1.2. This study

The current study was designed to extend previous research into visual behaviour of cyclists who listen to music. The first aim of the study was to examine to what extent listening to music affects glance behaviour of teenage cyclists. Teenage cyclists were of interest, since they listen to music more often than cyclists of other age groups. Furthermore, teenagers are particularly vulnerable from the perspective of cycling safety. There is a peak in cyclist fatalities among teenagers aged between 12 and 17, the age of increasing cycling autonomy (Candappa et al., 2012). In the previous studies into cyclists' visual behaviour (Ahlstrom et al., 2016; De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2010) the participating cyclists were older (range 16–26 years old). Teenagers, due to the immaturity of their brains and the great influence of the social environment, tend to take more risks in traffic than older road users (see e.g. Twisk, 2014). The visual behaviour of teenage cyclists may therefore also differ compared to older cyclists.

We chose to perform a study in real traffic and to use an eye-tracker to monitor cyclists' visual behaviour. This choice was dictated by the aspiration to obtain ecologically valid results and to determine location and duration of cyclists' visual effort. Other available research methods, including a field study or an observational study, could not be used due to a number of disadvantages. To start with, due to practical reasons observational studies are usually conducted at a limited number of locations and for a limited period of time, which can reduce the generalisability of results. Additionally, it is not always easy to determine whether the observed cyclist is listening to music, e.g. earbuds may not always be visible. Finally, with this method cyclists' visual attention can be determined only roughly, i.e. using head turns instead of eye movements. An eye-tracker is considered as an appropriate research tool to identify road users' visual attention (Velichkovsky et al., 2003). Although attention can be directed without moving the eyes, eye movements and visual attention are linked in most cases (see e.g. Mancas & Ferrera, 2016).

Secondly, we aimed to present our study as a case study explicitly addressing ethical issues related to performing an on- road study and to demonstrate dilemmas and consequences of this approach. Our focus is ethical issues related to protecting the welfare of research participants. Other ethical aspects, such as setting priorities for road safety research, although also important are beyond the scope of this paper. A number of ethical considerations were taken into account in the present study in order to minimize the risks. For example,

participants used their own bicycles and they were also free to choose their routes, departure and travel time – see *Section 5.2.1* for all ethical considerations applied in this study.

The third aim of the study was to examine to what extent the experimental set-up applied in this study is suitable to examine teenage bicyclists' visual behaviour in situations crucial for their safety. Unlike the study of Ahlstrom et al. where participants cycled along the same route, our experimental set-up allowed us to collect semi-naturalistic data of high ecological validity. Such an approach makes it possible to observe participants in a natural environment (Dozza, Werneke & Fernandez, 2012; Gehlert et al., 2012) but at the same time, it does not allow for control of the traffic environment. Therefore, it may be challenging to gather sufficient data on situations crucial for cycling safety. The present study aimed to evaluate this aspect. Another aspect investigated in this study was the performance of the eye-tracker and the quality of the data. The use of an eye-tracker in a natural setting can be challenging due to the fact that infra-red light of the sun can deteriorate the eye-tracker's capability to capture saccades (see e.g. Vansteenkiste, 2015). Therefore, in this study we also investigated the performance of the eye-tracker and the quality of the data.

5.2. Methods

5.2.1. Ethical considerations

For this study we applied stringent ethical criteria. In the Netherlands it is not mandatory for research institutes to obtain an ethical approval for the studies they perform. In 2015 SWOV Institute of Road Safety Research in the Netherlands, where the present research was conducted, decided however to establish an ethics committee. Precisely at the time when the data collection was about to start, an ethics committee was under development at our institute. For this reason, we were particularly aware of ethical considerations related to performing research with human participants. First, cyclists were included if they cycled regularly and if they frequently listened to music while cycling. Next, all participants (and in case of participants younger than 18 years old additionally their caregivers) signed an informed consent and could stop at any time during the experiment. Furthermore, the participants used their own bicycles and they were free to choose their route, departure and travel time. Finally, data collection was done in phases. After the first phase comprising 6 participants, preliminary analysis was performed to check whether cyclists

compensate for listening to music by increasing their visual performance. Given the small number of participants, this phase gave us just an indication of the expected results. The final decision considering whether or not to continue the data collection was therefore taken after the second phase in which the data of additional 8 participants was gathered. In case of adverse results, we were prepared to terminate the study. The target number of participants was at least 20 cyclists.

During the time of data collection we also carried out a literature study of research, field experiments and naturalistic cycling studies, performed with cyclists in real traffic. Our objective was to compare ethical considerations possibly addressed in previous studies with the ones we took into account in the present study – see *Section 5.3.1*.

5.2.2. Main experiment: effect of listening to music on cyclists' visual behaviour

Participants

Participants were recruited from a secondary school in the vicinity of SWOV Institute for Road Safety Research (The Hague, the Netherlands), through flyers and via informal contacts. Each participant received a gift voucher of €25.

Equipment and software

Eye-movements were recorded with a mobile eye-tracking headset (Pupil Pro, see (Kassner, Patera & Bulling, 2014) consisting of two built-in cameras (see *Figure 5.1*). A small and lightweight eye camera recorded the left eye at 30 Hz. A scene camera with a 90-degree horizontal field of view, mounted above the user's eye, recorded the forward road scene at 30 Hz. Both cameras were connected to a laptop which was carried in a rucksack. The data from the eye and the scene camera were combined using Pupil Software into one video file showing the scene camera footage with the glance data superimposed on the scene camera footage. Kinovea software (version 08.15) was used to extract, frame by frame, the duration of glance directions (Kinovea, 2014).



Figure 5. 1. The eye-tracker used in the present study.

Design and procedure

A within-subject design was used. Cyclists' glance behaviour, during two of their regular trips in urban environments, was monitored by a head-mounted eye-tracker. All trips were made in The Hague area. The route of the two trips was identical for a given participant (for example from home to school) but varied across the participants. During one of the trips, cyclists were listening to music of their choice and at their preferred volume (music condition); during the other trip they were 'just' cycling (baseline condition). The order of the conditions was randomised across participants. The data were collected by day- light and in dry weather. At the start of the route, the equipment was attached to the participant and the eye-tracker was calibrated. At the end of the route, the equipment was dismantled. After the second trip, the participants filled in a questionnaire including demographic measures (sex, age, and education), cycling habits, subjective risk perception and engagement in risk behaviour and incidents. Respondents were also asked to indicate how much they can hear when listening to music while cycling and how much a cyclist should hear to be able to cycle safely (response options: 1 = *nothing at all*, 2 = *not much*, 3 = *only loud or sharp sounds*, 4 = *most sounds*, 5 = *all sounds*) (see also Goldenbeld, Houtenbos & Ehlers, 2010; Stelling-Kończak, Hagenzieker & Van Wee, 2014).

Situations crucial for cycling safety

The choice of situations crucial for cycling safety in this study was dependent on which routes were chosen by the cyclists. We aimed for situations which are demanding and potentially risky for cyclists. We decided to focus on uncontrolled intersections, where no traffic lights or signs are used to indicate

the right-of-way. Cyclists at uncontrolled intersections should give way to traffic approaching from the right, according to the general rule applying in the Netherlands. There were two reasons for analysing the eye-tracker data at uncontrolled intersections. First, this type of intersections is relevant from the cycling safety point of view due to potential conflicts between cyclists and motorized vehicles. At uncontrolled intersections cyclists are usually not separated from motorized vehicles. This type of conflicts is important to study since young cyclists in the Netherlands are relatively often involved in a crash with a motorized vehicle (Reurings et al., 2012). Second, uncontrolled intersections were present in all routes travelled by the participants, providing us with sufficient data for the analysis. Our study focuses specifically on the glances to the right at uncontrolled intersections. This type of intersections requires cyclists to use their visual and auditory senses to check for the traffic approaching from the right - the direction to which cyclists should give way.

Data analysis

The video files for the music and baseline condition of each participant were examined to extract the segments including uncontrolled intersections. Glances to the right into an intersecting road with a minimum duration of 200 ms were included in the analysis. This duration was chosen as fixations longer than 200 ms can be related to attentive, focal processing while shorter fixations are considered pre-attentive (Velichkovsky et al., 2002). Glance behaviour was not encoded when the cyclist was stationary at an intersection (e.g. while yielding). For one participant, one intersection was excluded due to small changes of the route. For each participant and each uncontrolled intersection three performance indicators of visual behaviour were coded (see *Table 5.1*). The quality of the eye-tracker data turned out to be insufficient for only one trip. Therefore, similarly to Ahlstrom et al. (2016), in this case head turns inferred from the scene camera footage were used for this trip to code the cyclist' visual behaviour. Additionally, road infrastructure characteristics and traffic conditions were annotated for each intersection: i.e. presence or absence of a view obstruction, pedestrians, traffic approaching from the right and traffic approaching from the left. Two independent researchers coded the intersections. Twenty percent of the intersections was coded independently by both researchers. The Kappa inter-rater reliability statistic was 0.87 ($p < 0.05$) indicating a substantial agreement. The coders discussed and resolved discrepancies through mutual agreement.

Table 5.1. Performance measures of visual behaviour used in this study.

Performance measure	Description
Looking to the right	The number of intersecting roads to the right at uncontrolled intersections which the cyclist looked into out of the total number of intersecting roads to the right.
Mean number of glances	The summed mean number of glances towards the intersecting roads to the right.
Mean glance duration	The summed mean glance duration (<i>in milliseconds</i>) towards the intersecting roads to the right.

All statistical analyses were conducted using SPSS Statistical Software (version 23). The GENLINMIXED procedure was used to analyse the influence of music on whether or not a cyclist looked to the right into an intersecting road. Per participant each intersection was scored either 1 (a cyclist looked to the right) or 0 (a cyclist did not look to the right) and therefore the dependent variable was the number of intersecting roads which the cyclist looked into out of the total number of intersections encountered. Music and baseline condition was the within-subject factor. Since the dependent variable was not a continuous but a binomial variable, a standard repeated measures analysis of variance could not be applied. The generalized linear mixed models (GLMMs) analysis was performed instead with the summed looking to the right-score treated as a binomial variable with a logit link function. Generalized linear mixed models (or GLMMs) can be conceived of as a generalization of standard repeated measures analysis of variance models where the dependent variable is not necessarily continuous and normally distributed, but can also be a binary or binomial response, see for example Stroup (2013) for details.

The influence of music on the other performance measures (mean number of glances and mean glance duration) was analysed using separate standard repeated measures ANOVAs for each performance measure across the two conditions: music and baseline (the within-subject factor). A Wilcoxon Signed Ranks test was used to compare how much sound participants can hear while listening to music with how much sound they considered necessary to cycle safely (which were ordinal variables).

5.2.3. Evaluation of experimental set-up

Eye-tracker

Eye tracking performance outdoors may suffer from sunlight exposure. To avoid this problem many field studies with an eye-tracker collect data only in

cloudy weather. To our knowledge, the performance of the Pupil eye-tracker has not been evaluated yet in an outdoor environment. Therefore, with this study we aimed to fill this gap. The trips were made by day- light and in dry, but not necessarily cloudy weather.

Situations crucial for cycling safety

To investigate whether the uncontrolled intersections encountered by the participants were indeed demanding for cyclists, for each intersection, road infrastructure characteristics and traffic conditions were annotated i.e. presence or absence of a view obstruction, pedestrians, traffic approaching from the right and traffic approaching from the left. Two independent researchers coded the intersections.

5.3. Results

5.3.1. Ethical considerations

Literature overview

In total 12 studies, both field studies and naturalistic cycling studies were analysed. Four studies report obtaining ethical approval (De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2014; De Waard et al., 2010; Vansteenkiste, 2015). In the other eight studies (Ahlstrom et al., 2016; Dozza, Bianchi Piccinini & Werneke, 2016; Dozza & Werneke, 2014; Kircher et al., 2015; Langford, Chen & Cherry, 2015; Salmon, Young & Cornelissen, 2013; Schleinitz et al., 2017; Schleinitz et al., 2015) it is not clear whether ethical considerations were addressed: ethical approval is not reported, however, this does not necessarily mean that no ethical scrutiny was carried out.

Main experiment

Descriptive statistics of preliminary data, collected in the first phase of the experiment (based on 6 participants), were similar for the baseline and music conditions. Due to the small sample size, no statistical tests were performed in the first phase. In the second phase, data from additional 8 participants was gathered. The results based on the data gathered in the first and the second phase ($N = 14$) revealed no increase in visual performance while cycling with music (see *Section 5.3.2*). On the contrary, many participants in the music condition showed a decrease in visual performance. Given the adverse results, the experiment was stopped at that point (see also *Section 5.4.1*).

5.3.2. Main experiment: effect of music on cyclists' visual behaviour

Participants

In the end, fourteen cyclists (7 females) aged 16–18 years ($M = 17.1$; $SD = .5$) participated in this study. Participants spent on average about 6.5 h cycling per week ($M = 394$ min). On average, they were listening to music during 70% of all of their trips.

Visual behaviour

The results are based on the data gathered by the whole sample ($N = 14$). Table 5.2 contains descriptive statistics for the three performance measures analysed in this study. On average less than half of intersecting roads to the right received cyclists' glances ($M = 0.490$ in the baseline and $M = 0.406$ in the music condition, see Table 5.2). None of the performance measures differed significantly between the baseline and music conditions indicating that cyclists' visual behaviour was not significantly influenced by listening to music.

Table 5.2. Descriptive statistics: M and (SD) for the three performance measures (see Table 5.1 for the description of the performance measures.)

	Baseline	Music
Looking to the right	0.490 (0.328)	0.406 (0.296)
Mean number of glances	4.07 (3.7)	3.71 (4.4)
Mean glance duration (in <i>ms</i>)	500.1 (298.5)	648.9 (397.5)

Although overall visual behaviour between the music and the baseline condition was not statistically different, descriptive analysis (see Table 5.3) showed that 21–36% of the participants increased their visual performance in the music condition. A higher percentage of participants, 43–64% decreased their visual performance while listening to music.

Table 5.3. Percentage participants who increased or decreased visual performance in the music condition (%).

	Increased visual performance	Decreased visual performance
Looking to the right	21.5	57
Mean number of glances	21.5	43
Mean glance duration (in <i>ms</i>)	36	64

5.3.3. Final results: self-reported measures

Participants indicated that they could hear as much sound as they considered necessary to cycle safely. The Wilcoxon Signed Ranks test revealed no significant differences between the ratings of how much sounds could be heard while listening to music and the ratings of how much sound is considered necessary to cycle safely.

Due to the limited sample size, statistical analyses were not performed to examine the association between glance behaviour and self-reported measures. Computing pairwise correlations between all these variables creates the problem of chance capitalization due to multiple pairwise comparisons. An alternative approach can be performing a categorical principal component analysis (CATPCA). CATPCA is a data reduction technique appropriate for categorical and ordinal variables. It is used to identify the underlying components of a set of items while maximizing the amount of variance accounted for in those items. Since this technique requires 5 to 20 times as many participants as variables, it could not be applied in this study either.

5.3.4. Evaluations of experimental set-up

Eye-tracker

Results show that although some of the trips took place in sunny weather, the eye-tracking data was not disturbed by the infra-red light of the sun. As already mentioned good quality eye-tracking data was obtained. Only one trip (out of 28) resulted in insufficient quality of the eye-tracking data due to poor calibration.

Situations crucial for cycling safety

On average the trips lasted for 13 min. The number of uncontrolled intersections encountered by the participants varied from 2 to 17 ($M = 7.6$, $SD = 4.6$). At the intersections cyclists either went straight on (in 85% of all intersections) or turned left.

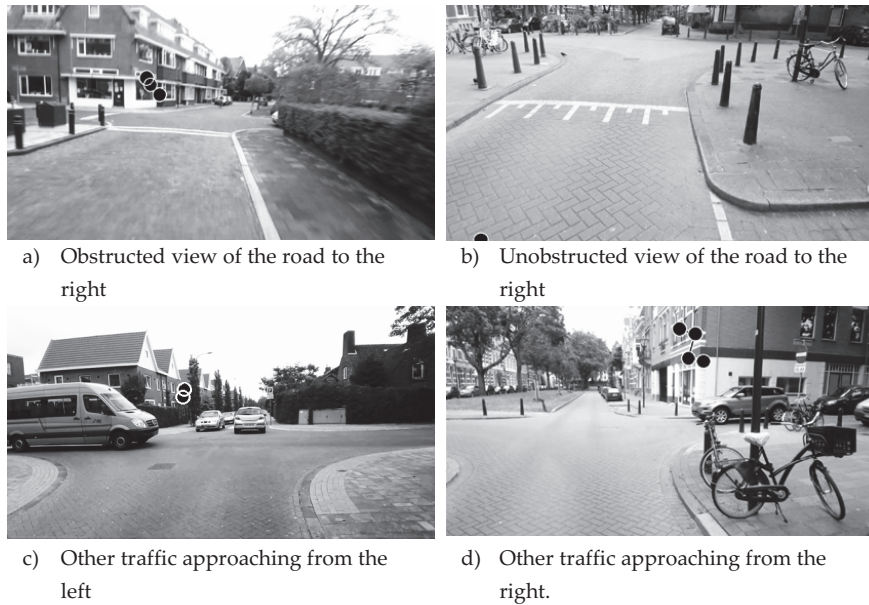


Figure 5.2. Examples of uncontrolled intersection analysed in this study. The dots indicate the eye positions of the cyclist and the line connects the eye positions in temporal order.

These were mainly roads in residential districts and urban access roads. Most of them had not any dedicated cycle facilities (see *Figure 5.2* for examples). At 8% of all intersections other traffic was approaching from the right. This was often a passenger car (53% of all cases). At 4% of the intersections other traffic, often a cyclist (57% of all cases), was approaching from the left. Traffic densities at the intersections were rather low. Cyclists encountered especially pedestrians, motor vehicles and other cyclists. Only at 16% of all intersections the view of the road to the right was unobstructed.

5.4. Discussion

The current study compared the visual behaviour of teenage cyclists at uncontrolled intersections in two conditions: while listening to music and while 'just' cycling. To our knowledge this is the first study gathering semi-naturalistic data to investigate visual behaviour of teenage cyclists while listening to music. The aims of the study were: 1) to investigate whether cyclists listening to music increase their visual performance, 2) to present our

study as a case study explicitly addressing ethical issues related to performing an on-road study and 3) to evaluate the data collection methodology applied in this study.

5.4.1. Main experiment: effect of music on cyclists' visual behaviour

Our first aim was to investigate whether and to what extent cyclists change their visual behaviour while listening to music. Because listening to music impairs cyclists' auditory perception, cyclists may attempt to compensate for the decreased auditory input by increasing their visual performance. Our results showed that cyclists often failed to look to the right into the intersecting road, irrespective of whether or not they are listening to music. Although at the uncontrolled intersections cyclists were required to yield to the traffic coming from the right, only 45% of the intersections received cyclists' glances.

The finding that intersecting roads to the right often failed to capture cyclists' attention raises concerns. To illustrate, consider the following situation: a cyclist approaches an uncontrolled intersection and at the same time another road user approaches from the right on a collision course with the cyclist. It is crucial that the cyclist's attention is directed to the right. Attention selection may be driven by top-down expectations: even if the other road user is outside the cyclist's field of view, the cyclist may expect main hazards to come from the right based on his or her knowledge of and experience with uncontrolled intersections. If the cyclists' attention to the right is not captured in the top-down manner, visual features of the road user, e.g. movement, in the right field of view may still draw the cyclists' attention (bottom-up attention selection). In case of approaching 'non-silent' road users (e.g. conventional cars), their sound can additionally act as an attentional trigger facilitating their detection and localisation.

The question is, however, whether the bottom-up visual and/or auditory attention selection will provide cyclists enough time to react properly. An approaching road user may capture cyclists' attention too late because of visibility obstruction or cyclist's looking to the left or backwards. Recent studies using naturalistic cycling data show indeed that intersections with an obstructed view increase cyclists' risk of experiencing a critical event (Dozza & Werneke, 2014). Furthermore, with the increasing number of quieter, hybrid or electric vehicles on the road, the sound of the vehicle may not capture cyclists' attention early enough to afford a proper reaction (see Stelling-Kończak, Hagenzieker & Van Wee, 2015).

In the present study, cyclists' visual behaviour was not affected by listening to music. In the field experiment by Ahlstrom et al. (2016), similar results were found although the traffic environment in that study was less demanding than the one we focused on in our research. As already mentioned, cyclists in the study of Ahlstrom et al. were riding along a cycle track which had priority over the four intersecting side roads. In contrast, cyclists in our study were required to yield to the traffic coming from the right. The cyclists in both studies may have felt confident in traffic and felt no need to compensate for the limited auditory input. As shown, cyclists in our study reported that they could hear as much sound as they considered necessary to cycle safely. This finding is in line with recent research in which cyclists in cities where a cycling culture is established (such as cyclists in our study) reported feeling less fear of traffic, less frequent helmet use and being more often distracted than cyclists in emerging cycling cities (Chataway et al., 2014).

The results of the present study should, however, be treated with caution due to the limited sample size. The relatively small sample size may have reduced the ability to detect small effects between the baseline and music conditions. Therefore, we realize that our study cannot provide strong evidence for the absence of visual compensation among cyclists who listen to music. However, if the absence of visual compensation reflects a true tendency, cyclists listening to music could be expected to be at more risk than cyclists who 'just' cycle. This because cyclists' attention may not be directed in a bottom-up manner towards a vehicle appearing in the periphery. Peripheral vision is normally very sensitive to contrast and motion and serves as an early warning system for moving targets entering the visual field (see e.g. Duchowski, 2003). Fundamental research shows, however, that visual attention is no longer captured by abrupt visual stimuli when a concurrent auditory task is present (Boot, Brockmole & Simons, 2005). Additionally, as already mentioned in the introduction, the sound of an approaching vehicle may get masked by music and therefore fail to capture cyclists' attention.

It is also worth mentioning that although overall visual behaviour between the music and the baseline condition was not statistically different, there seemed to be three distinct groups of cyclists: those who decreased their visual performance while listening to music, those who increased their visual performance; and those whose visual behaviour was not affected by listening to music. It will be valuable in future work to explore characteristics of these groups. The group who decreased their visual performance was the largest in our study – it consisted of 43–64% of the participants (depending on the

performance measure). If the trend were to continue with a larger sample, a significant effect may be found in the 'risky' direction. Being aware of that possible effect of cyclists decreasing their visual attention while listening to music, we felt obligated to protect our teenage participants.

5.4.2. Ethical considerations

Our second aim was to present this study as a case study explicitly addressing ethical issues related to conducting a study in real traffic (see *Section 5.2.1*). To avoid exposing participants to potential risks related to cycling whilst listening to music, the cyclists in our study used their own bicycles and they were free to choose their own routes, travel and departure time. Furthermore, only those cyclists were included in our study who cycled regularly and who frequently listened to music while cycling. Finally, when the results indicated that a substantial percentage of participants cycling with music (43–64% depending on the visual performance measure; see also *Table 5.3*) decreased their visual performance, we decided to terminate the study. As a result, our sample was limited to fourteen cyclists, which might explain why listening to music did not significantly affect cyclists' visual behaviour. It is, however, still possible that cyclists do change their visual behaviour when listening to music, but this change can only be detected with larger samples. An ethical dilemma arises: should people be exposed to potentially risky situations in the pursuit of significant results?

To date ethical considerations related to performing a study in real traffic have not been systematically and explicitly reported in transport and traffic safety journals. Furthermore, no clear international ethical standards appear to exist for traffic research. It is therefore unclear how various researchers in this field deal with the ethical issues related to protection of research participants. As shown in *Section 5.1.1* not all traffic researchers are obliged to obtain an ethical approval (depending where the study is carried out) and even if a particular study has been approved by an ethical committee, it does not necessarily mean that another ethics committee would reach the same conclusions. Except for the reduction of risks for research participants, clear ethical standards ensure equal opportunities for traffic researchers at various universities and research institutes to conduct a 'publishable' study (see also *Section 5.1.1*).

We hope this study contributes to the discussion about the research ethics involved in road safety research and illustrates the dilemma related to conducting a study in real traffic. It is extremely challenging to investigate cyclists' visual behaviour in ecologically valid conditions without inflicting

potential dangers to participants. Can this dilemma be avoided by studying behaviour with the use of other research methods? From an ethical perspective, laboratory studies, providing a safe setting for participants, are preferable. There may be, however, some differences in how people distribute their visual attention in the natural environment compared to the laboratory setting. To illustrate, glance behaviour of pedestrians in the real world was found somewhat different than in the lab (Foulsham, Walker & Kingstone, 2011). This is because cycling outdoors requires steering, pedalling and maintaining balance whilst monitoring the environment and the road quality (see for example Vansteenkiste, 2015). Furthermore, differences between laboratory and real-world settings can arise due to various sounds that are typically present in real traffic situations only, e.g. traffic sounds, wind noise, aerodynamic noise caused by the head of a cyclist moving through the air, people talking on the sidewalk or other loud masking noises. The reproduction of these real life cycling conditions in a laboratory setting is not an easy task. Only a few bicycle simulators in the world are high-fidelity immersive simulators offering realistic motion and visual experience as well as auditory information (see e.g. Plumert et al., 2011; Scherfgen et al., 2013). However, visual behaviour of cyclists in a bicycling simulator has not been validated yet against the behaviour of cyclists in real traffic (see e.g. Englund, Nilsson & Voronov, 2016). It is also not known whether the simulation of the natural sounds provided by bicycle simulators is valid for the listener. Therefore, the relevance of bicycle simulators in studying cyclists' visual behaviour needs yet to be established. It is also worth mentioning that validation research, although necessary to verify the usefulness of a bicycle simulator, requires data collection in real traffic, which again generates ethical issues.

Other available research methods, i.e. surveys and observational studies, have important disadvantages. Surveys rely on accuracy of memory and honesty of reporting and may reflect what people think they do, rather than their actual visual behaviour. Furthermore, this method cannot provide quantitative evidence on the location and duration of cyclists' visual effort. Observational studies usually use hidden cameras. Observations are often conducted at a limited number of locations and for a limited period of time, which can limit the generalisability of results. Additionally, with this method cyclists' visual attention can be determined only roughly, i.e. using head turns instead of eye movements. Finally, it is also not always easy to determine whether the observed cyclist is listening to music, e.g. earbuds may not always be visible.

5.4.3. Experimental set-up

The third aim of the present study was to evaluate to what extent the experimental set-up applied is suitable to examine bicyclists' visual behaviour in situations crucial for their safety. We were especially interested in two aspects. The first aspect was the performance of the eye-tracker. The other aspect related to the question whether uncontrolled intersections, selected in this study as situations crucial for cycling safety, were demanding traffic situations for cyclists.

Results show that the use of an eye-tracker by cyclists who choose their routes and commuting time was feasible. Good quality eye-tracking data was gathered. The eye-tracking data was not disturbed by the sunlight although some of the trips took place in sunny weather conditions. It is worth mentioning that we assumed, as in other eye-tracking studies, that eye-movements denote visual attention. The relationship between eye movements and visual attention is controversial and subject to common criticism as it is possible to dissociate attention from eye movements (see e.g. Engbert & Kliegl, 2003; Hagenzieker, 1992). Nevertheless, psychological evidence indicates that attention and eye movements are closely related (see e.g. Duchowski, 2003). We expect that in our study cyclists' eye movements denoted their visual attention, but we acknowledge awareness of the fact that it may not always be so. Furthermore, given the nature of eye-tracking technology measuring where a person's fovea²⁰ is directed, the present study has not taken into account the role of peripheral vision. This could be considered a limitation of this study. When at uncontrolled intersections, cyclists' fovea is not directed to the right, an approaching road user appearing in the right visual periphery can, due to its visual features, still capture cyclists' visual attention. However, relying on peripheral vision may not be a safe strategy to negotiate intersections: cyclists may have less time to react, obstructed view may prevent cyclists to effectively use their peripheral vision and concurrent auditory task may inhibit cyclists' attentional capture (see also *Section 4.1*).

As already mentioned in the introduction, the semi-naturalistic approach chosen in this study gives researchers the opportunity to observe participants in a natural environment, but at the same time it does not allow for the control of traffic environment, e.g. traffic densities. Results of this study show that the traffic densities at the intersections were rather low. Only at 8% of all intersections other traffic was approaching from the right. Uncontrolled

²⁰ The fovea is a small part of the eye responsible for our sharp, colourful vision.

intersections, which were the focus of this study, although requiring cyclists to be alert for other traffic, especially for traffic approaching from the right, were probably, due to the low densities, not very demanding for cyclists. Cycling in heavy traffic, especially navigating through a roundabout or an intersection or crossing over, would obviously be more demanding. However, these traffic situations are often regulated by the Dutch cycling infrastructure, which is characterized by extensive and safe cycling facilities. Cyclists in the Netherlands still encounter complex situations; however, the presence and frequency of these situations could not be controlled while collecting (semi-) naturalistic data. Therefore, we may conclude that the methodology used in this study is less suitable to study glance behaviour of teenage cyclists in demanding traffic environment.

5.4.4. Conclusion

The popularity of listening to music among teenage cyclists has raised concerns about the impairment of auditory perception and its potential impact on cycling safety. Not being able to hear traffic sounds may decrease cyclists' awareness of approaching vehicles and lead to unsafe situations. The question is whether cyclists compensate for the decreased auditory input by increasing their visual attention. The current study addressed this question by collecting semi-naturalistic data. At the same time we explicitly addressed a number of ethical issues related to performing a study in real traffic.

Although this study found that listening to music does not significantly affect cyclists' visual behaviour, we cannot exclude that the effects do exist and can be found with a larger sample or in other, e.g. more demanding traffic environment. Future studies may wish to explore glance behaviour of (teenage) cyclists listening to music on a larger scale and in more demanding traffic situations. Semi-naturalistic data used in this study turned out to be less suitable to study glance behaviour of teenage cyclists in demanding traffic environment. Additionally, the methodology used in this study did not allow us to study cyclists' behaviour in a demanding traffic environment. At this moment, no other research methods seem suitable to address this research gap. Available methods have all disadvantages, either methodological or ethical.

This study showed fundamental ethical dilemmas involved in traffic safety research. We feel it is necessary that clear international ethical standards are developed and implemented within road safety research for a number of reasons. First of all, ethical standards are important to protect participants

from risks. Next, ethical standards offer clear and equal opportunity for all researchers to conduct empirical studies and to have papers accepted for publication. Finally, ethical standards may stimulate the development of new research methods which will allow for gathering quantitative data in ecologically valid conditions without posing risks to participants.

6. Discussion and conclusion

Navigation through traffic is mainly a visual task. However, for cyclists auditory information may also be of great importance. Not only salient warning sounds such as a horn honking, but also pavement, tire and engine noise can inform a cyclist about the presence and location of approaching vehicles. Auditory cues seem to be especially essential in situations when visual information is less available, i.e. for areas outside a cyclist's field of view, when visibility is obstructed or when a cyclist is (visually) distracted. Although the importance of auditory information for the safety of cyclists and pedestrians has been stressed in the last two decades, only recently has this subject received scientific attention. This attention has mainly been drawn by the concerns regarding road users' use of mobile phones and the quietness of electric cars. Studies in the field of auditory perception of road users have mainly investigated the importance of auditory cues for pedestrian safety. Therefore this thesis focused on cycling safety and aimed to answer the following research questions:

1. To what extent does listening to music and conversing on the phone impact cyclists' auditory perception and safety?
2. To what extent do acoustic properties of (hybrid) electric cars pose a safety hazard for cyclists?

The two research questions were investigated for three age groups: teenage cyclists aged 16-18, adult cyclists aged 30-40 and older cyclists aged 65-70.

This chapter will discuss the main findings of the research conducted throughout this thesis and their implications for cycling safety. In *Sections 6.1* and *6.2* the research questions are answered. *Section 6.3* discusses the implications of the research findings presented in this thesis. *Section 6.4* discusses the limitations of the research and suggests directions for further research. The final section provides the conclusions that can be derived from this thesis.

6.1. Listening to music and conversing on the phone while cycling

6.1.1. Prevalence

The results of the Internet survey presented in *Chapter 4* show that the use of mobile phones among cyclists is quite popular, especially among young cyclists. Compared to adult and older cyclists, teenage cyclists are the most frequent users of a mobile phone. For teenage cyclists, listening to music is the most popular type of a mobile phone use. A great majority (77%) of teenage cyclists reports listening to music during at least some trips while almost a quarter of cyclists in this age group listens to music on each trip. Having a phone conversation is less popular among teenage cyclists: 63% of them converse on the phone, but only about 2.5% on each trip. Among adult and older cyclist the percentages of those who listen to music and those who talk on the phone were almost equal: about 55-60%. However, older cyclists rarely used a mobile phone: only 6-10% of them reported using a mobile phone. Furthermore, the percentage of adult and older cyclists who converse on the phone or listen to music on each trip was very low.

These findings are to a great extent in line with recent observational studies, which show that younger cyclists in the Netherlands are more frequent users of a mobile phone than older cyclist (Broeks & Zengerink, 2016; De Waard, Westerhuis & Lewis-Evans, 2015). Cyclists were more often observed to listen to music (17% of the cyclists) than to talk on the phone (3% of the cyclists). Listening to music was observed among 15-17% of cyclists and it was especially popular among teenagers and young adults (Broeks & Zengerink (2016). There are some indications that the use of devices among cyclists in the Netherlands is increasing. Broek & Zengerink report that the share of cyclists observed to use devices grew from 19% in 2015 to 24% in 2016. This increase was mainly due to the increased share of cyclists who listen to music, from about 13% in 2015 to 17% in 2016.

6.1.2. Effects on auditory perception

Given the popularity of mobile phone use while cycling, concerns about cyclists' auditory perception seem justified. Previous research, discussed in the literature review presented in *Chapter 2* (see *Section 2.5.1*), shows indeed that both listening to music and conversing on the phone negatively affects cyclists' auditory perception of a bicycle bell. The impact of high tempo music, loud music and music listened through in-earphones is even higher as such

music also impairs the hearing of loud sounds i.e. a horn honking. Interestingly cyclists auditory detection was not affected when they used one earphone to listen to music (De Waard, Edlinger & Brookhuis, 2011).

Except for warning sounds, such a bicycle bell and a horn, it may also be important for cyclists to detect and localise approaching cars. To our knowledge no studies are available into the extent to which listening to music or conversing on the phone impairs cyclists' auditory perception of approaching cars. However, a recent laboratory study with pedestrians suggests that having a phone conversation may increase vehicle detection times (Davis & Barton, 2017). Furthermore, fundamental research shows that speech and music negatively affects auditory localisation of various sounds, including warning traffic sounds (May & Walker, 2017). Interestingly, the negative effects were found regardless of whether listeners ignored or attended to speech or music pointing at masking rather than auditory distraction as a cause of these effects. May and Walker found that listening to speech accompanied with music (which is similar to listening to music with lyrics) had a more detrimental effect on auditory localisation than listening to speech only. According to the authors these findings can be explained by a greater range of frequencies of the masking sound present in music with lyrics. Masking is indeed more likely when a sound possesses similar frequency range as the masked sound (see also *Section 2.3, 4.1 and 5.1*).

We can assume that the negative effects of listening to music and conversing on the phone studied by Davis and Barton (2017) and May and Walker (2017) also apply to cyclists, though, some caution is needed. Undoubtedly, there are some differences between cyclists and static listeners used in above-mentioned studies. Cyclists, for example, are typically in motion and have to deal with aerodynamic noise caused by the head displacement through the air (see also *Section 6.4.1*).

6.1.3. Safety risk

Since listening to music and conversing on the phone impair cyclists' auditory perception and cycling behaviour (see also *Section 2.5.1*), it could be expected that engaging in these activities negatively affects cycling safety. Surprisingly, the Internet survey presented in *Chapter 4* found no relationship between the frequency of listening to music or conversing on the phone among teenage cyclists on the one hand and their involvement in incidents on the other hand. Similarly a retrospective survey in the Netherlands comparing cyclists who had a bicycle crash with cyclists who had not had a bicycle crash shows that

conversing on the phone was not associated with an increase in the crash risk (VeiligheidNL, 2017)²¹. The relationship between listening to music and bicycle crashes was not investigated in that study.

It is difficult to determine to what extent this lack of relationship between listening to music and conversing on the phone on the one hand and crashes or incidents on the other hand may be due to cyclists' compensatory strategies. This difficulty is related to the fact that the results of the surveys or questionnaires are not always confirmed by studies in real traffic. Cyclists who use their mobile phone do report applying compensatory strategies. In the Internet survey presented in *Chapter 4* about two-thirds of teenage cyclists reported adapting their behaviour to compensate for listening to music or talking on the phone. The most often reported compensatory strategies for listening to music were: looking around more frequently, turning the music down or off, and using one earphone instead of two. Compensatory behaviour for conversing on the phone mainly involved decreasing cycling speed, keeping the conversation short and looking around more frequently.

Field experiments only partly confirm these findings. To start with, cyclists who were having a phone conversation were indeed observed to decrease their speed (De Waard, Edlinger & Brookhuis, 2011; Kircher et al., 2015). By reducing their speed, cyclists may compensate for the high task demand related to the phone conversation. Lower speed gives cyclists more time to react. Decreasing speed has generally a positive effect on traffic safety²². However, the self-reported increase in visual performance has not been confirmed by studies using eye-tracking technology to monitor cyclists' glance behaviour in real traffic. Specifically, teenage cyclists who were listening to music or conversing on the phone were not observed to increase their visual performance (i.e. look around more frequently). On the contrary, in a field experiment of Ahlstrom et al. (2016) cyclists who were calling were found to slightly decrease the number of glances and the total glance duration to relevant targets and to mainly reduce the glances to less relevant targets. In the same field experiment, as well as in the study presented in *Chapter 5*, listening to music was not found to affect cyclists' visual behaviour.

²¹ The study compared more than 2,000 cyclists who attended the Accident & Emergency Department after they had had a bicycle crash with more than 1,800 cyclists who had not had a bicycle crash.

²² Too low speeds may, however, be risky for cyclists. At low speeds more effort is needed to stabilize the bicycle and cyclists' lateral control is decreased.

The contradiction between the findings of the Internet survey and results of studies in real traffic could be related to the difference in the studied traffic environment. The Internet survey concerned cycling behaviour in general, while the field studies were performed in specific, relatively undemanding traffic environment. It is possible that cyclists who listen to music or converse on the phone do increase their visual attention only in some, for example more demanding traffic situations. Finally, surveys generally rely on what people think they do rather than their actual behaviour (see also *Section 6.4.1* discussing methodological limitations in more detail).

To sum up, listening to music and talking on the phone is widespread among cyclists. Although engaging in these activities negatively impacts cycling behaviour and auditory perception of relevant traffic sounds, neither listening to music nor talking on the phone was found to increase the risk of getting involved in a self-reported incident. It is possible that decrements in cycling behaviour and auditory perception caused by listening to music and conversing on the phone are compensated by cyclists themselves or by other road users involved. It is, however, difficult to determine to what extent cyclists who listen to music or talk on the phone engage in compensatory behaviour as the research findings into this subject are mixed.

6.2. (Hybrid) electric cars

6.2.1. The growing number of (hybrid) electric cars

Although electric cars are still relatively rare on our roadways, their number continues to increase globally. In 2015 the global electric car stock (comprising of battery electric and plug-in hybrid electric cars) surpassed 1 million vehicles and in 2016 already 2 million²³. In 2016 the Netherlands had the second highest electric market share (after Norway)²⁴ (OECD/IEA, 2017). The number of electric cars is expected to increase sharply. The Paris Declaration on Electromobility and Climate Change and Call to Action sets a global target of 100 million electric cars (20% of all road vehicles) by 2030 (OECD/IEA, 2016) for the supporting partners²⁵ (including businesses and organizations in many countries around the world). Meeting the target requires individual countries

²³ The electric car stock is primarily estimated on the basis of cumulative sales since 2005 (see OECD/IEA, 2017).

²⁴ In the Netherlands 6.4% of newly registered cars in 2016 were electric, in Norway 29%.

²⁵ http://climateinitiativesplatform.org/index.php/Paris_Declaration_on_Electromobility_on_Climate_Change.

to set ambitious sales targets for electric cars in the near future. The Netherlands, for example, intends to have all new cars emission-free by 2030. In 2017 (hybrid) electric cars constituted only 3% of the total car stock in the Netherlands.

6.2.2. The quietness of (hybrid) electric cars

With the growing number of (hybrid) electric cars on the road, concerns grew about their quietness constituting a safety hazard for pedestrians and bicyclists. Research into acoustic properties of (hybrid) electric cars presented in the literature review in *Chapter 2* shows that when driven at low speeds these cars generally produce less noise than conventional cars. When driven 10 km/h (hybrid) electric cars were 2-8 dB-A quieter and at 15-30 km/h they were 2-3 dB-A quieter than conventional cars. Above 20-30 km/h no differences in sound intensity were found, most likely because the tyre-road noise becomes dominant at these speeds and not the engine noise.

As shown in the literature review in *Chapter 2*, differences in acoustic properties between (hybrid) electric and conventional cars influence detectability of the vehicles. Generally, (hybrid) electric cars remain undetected longer by pedestrians than conventional cars, especially when the cars are driven at low speeds and in low ambient sound. Research showed that (hybrid) electric cars were often detected too late to afford a safe crossing. Not only are (hybrid) electric detected later than conventional cars, they are also localised less accurately. The results of the laboratory study presented in *Chapter 3* show that electric cars, especially when driven at low speeds, were localised less accurately than conventional cars by teenagers, adults and the elderly. The elderly, however, performed even less accurately than the other age groups.

Detection and localisation problems related to slow-moving (hybrid) electric cars are confirmed by studies among drivers of electric vehicles showing that cyclists have problems with hearing these vehicles, especially when they are driven at low speeds (for the details of the studies with drivers of electric cars see literature overview presented in *Chapter 2, Section 2.5.6*). A substantial percentage of drivers (45-67%) in these studies reported being involved in one or more noise-related incidents involving cyclists or pedestrians.

6.2.3. Crash risk

Given the negative impact of slow-moving (hybrid) electric cars on auditory perception of cyclists and pedestrians, concerns about the safety risk for these vulnerable road users seem justified. As described in the literature review in *Chapter 2* the safety performance of electric cars cannot, however, be easily compared with that of conventional cars. The main difficulty is related to missing data on the share of kilometres driven by electric cars in comparison to conventional cars.

If the quietness of vehicles were a contributory factor to crashes, the differences between conventional and electric cars should be expected to manifest themselves at low speeds, where detectability and localisation problems were found. Therefore, to determine whether the quietness of (hybrid) electric cars increases the risk of crashes involving cyclists and pedestrians, for each car type (conventional and electric) specific data on the share of kilometres driven at low speeds will be needed as well as data on the share of crashes occurring at low speeds. Finally, specific characteristics of (hybrid) electric car drivers, e.g. extra concern for the environment, or car condition – generally newer and having higher safety standards than the mix of conventional cars - may influence their crash involvement. To date no study into the safety risk of quiet (hybrid) electric cars has taken these aspects into account.

It is important to note that the potential risks associated with the quietness of electric cars may be, at least to some extent, mitigated by drivers of these cars. A driving simulator study of Cocron et al. (2014) suggests that drivers of electric cars are aware of potential noise-related hazards and they compensate for the quietness of their cars. Given the limited number of studies in this field, more evidence is, however, needed before we can conclude that drivers of electric cars compensate sufficiently for the potential risks associated with the quietness of their cars.

To sum up, electric cars are detected later and localised less accurately than conventional cars, especially when driven at low speeds and in low ambient sound. Due to missing exposure data it is unknown whether electric cars increase the risk of crashes involving cyclists. The potential risks associated with the quietness of electric cars at low speeds may be, at least to some extent, mitigated by compensatory strategies of drivers of these cars.

6.3. Implications

6.3.1. Reliance on auditory information

Auditory perception of traffic sounds and vehicle movement may be crucial for cyclists, especially for gathering information about approaching traffic from areas outside one's field of view or when visibility is obstructed. The results presented in this thesis suggest however, that in moderate or high ambient sound, it may be very difficult for cyclists to timely perceive approaching cars solely from auditory information. As discussed in *Chapter 2*, if the ambient noise is too high in relation to the car sound output, car sounds remain undetected or become detected at very short distances. Furthermore, as shown in *Chapter 3*, in moderately high ambient noise car sounds are localised less accurately than in low ambient sound. Even with low ambient sound, cyclists' auditory perception of approaching vehicle may be adversely affected by the presence of other vehicles in near vicinity. A recent study of Ulrich, Barton & Lew (2014) showed that auditory detection and localisation of an approaching car was impaired by the sound of another vehicle travelling at the same speed in otherwise low ambient sound level.

The ambient noise or the sound of other vehicles may simply mask the sound of an individual car. Quieter sounds are generally masked by louder sounds. The higher the sound intensity of the masking sound, e.g. ambient noise or other vehicle, the higher the intensity level of the masked sound, e.g. car sound must be before it can be detected (see e.g. White & White, 2014). High ambient sound or loud cars are therefore more likely to mask cars operating at low noise levels, i.e. generally cars driven at low speeds but especially slow-moving electric cars.

Traffic settings with moderate or high ambient noise or with multiple approaching cars may pose a risk for cyclists relying on auditory cues. Shorter detection times and less accurate localisation of approaching cars may lead to errors in judgement and unsafe cycling manoeuvres. Therefore cyclists' reliance on auditory cues alone should be discouraged. For example, equipping bicycles with mirrors could help cyclists to use their vision to gather information about traffic approaching from behind. At the same time the traffic environment should be designed in such a way that cyclists are not forced to rely on auditory perception, for example by providing an unobstructed view for cyclists.

6.3.2. Older cyclists' problems with auditory perception

As mentioned in *Chapter 1* the elderly represent a significant proportion of cyclist casualties in Europe and therefore this age group warrants special attention. Cyclists over 65 years old constitute 44% of all cyclist fatalities across the EU-countries (European Commission, 2017a). As a result of a cycling crash, the elderly run a relatively high risk of dying or sustaining serious injuries. The high fatality rate of the elderly has been related to their frailty, particularly to the combination of higher brittleness of the bones, decreased elasticity of soft tissue and weakened locomotive functions, but also to age-related declines in sensory and cognitive functions (Davidse, 2007; Evans, 2001; Weijermars, Bos & Stipdonk, 2016).

The results of studies presented in this thesis suggest that making use of auditory cues for older cyclists may be more challenging than for younger cyclists. Older age was associated with lower percentages of detected cars (Mendonça et al., 2013). Furthermore, results presented in *Chapter 3* showed that the elderly exhibited less localisation accuracy than teenage or adult cyclists. It is difficult to determine what causes the decrements of auditory performance among older people. The diminished performance of older adults could result from peripheral impairments, i.e. impairments reflecting age-related changes in the outer, middle and inner ear primarily manifested by decrements in hearing acuity. We have seen in *Chapter 3* that almost all participants without hearing loss performed well, while only some participants with hearing loss were impaired. These findings could suggest that certain type or degree of hearing loss may have caused localisation problems among older adults. Fundamental research suggests that high frequency hearing loss, which is typical of older age, does not impair localisation of static broadband sounds in the horizontal plane (van Opstal, 2016 p. 409-410). It is, however, unknown what the impact is of high-frequency hearing loss on spatial motion perception. Unfortunately, to date, no studies have addressed this subject, see also (Carlile & Leung, 2016).

Except for possible peripheral impairments, the diminished ability of older adults to localise sounds of moving cars could be related to difficulties with more complex auditory processing like locating and tracking sound sources for which central processing is required (see e.g. van Opstal, 2016). Fundamental research suggests that also the central temporal processing

capacities (ITD processing²⁶) deteriorate with age (Dobрева, O'Neill & Paige, 2011). Finally, localisation problems of the elderly could also be related to other functional limitations related to aging, such as declines in visual functions, fluid intelligence, speed of processing, working memory or other motor functions (see also *Chapter 4, Section 4.1*).

Knowing what causes localisation problems of older road users may help to develop effective countermeasures. To illustrate, equipping electric vehicles with add-on sound may not necessarily ensure better detectability and increased localisation among older cyclists, if their decrements in auditory performance are not related to hearing loss (see also *Section 6.3.4* on add-on sounds). Therefore future studies should explore auditory detection and localisation of moving sounds among older adults.

6.3.3. Listening to music versus conversing on the phone

From the perspective of auditory perception, we should be more concerned about cyclists listening to music than talking on the phone. First of all, as shown in the Internet survey presented in *Chapter 4*, listening to music is very popular among cyclists, especially teenagers - far more popular than conversing on the phone. The same study indicates that teenage cyclists can hear less sound when they listen to music than when they talk on the phone. This finding is in line with previous studies showing that although both activities impaired auditory perception of a bicycle bell, listening to music additionally can impair cyclists' auditory perception of very loud sounds, such as a horn honking.

Furthermore there are indications that auditory localisation of traffic sounds is to a greater extent impaired by listening to music than by talking on the phone. Fundamental research shows that listening to music accompanied with speech (similar to listening to music with lyrics) is more detrimental for auditory localisation of environmental sounds (including traffic alert sounds) than listening to speech only (May & Walker, 2017).

²⁶ Interaural time difference (ITD) relates to a time difference in the sound arriving at two ears (see e.g. Baldwin, 2012).

6.3.4. The proposed solutions may not be effective

A number of solutions have been proposed to mitigate the reduction of auditory cues available for cyclists. To start with, various types of headphones have been designed allowing for simultaneous listening to music and surrounding sounds, e.g. bone conduction headphones allowing for listening to music without blocking the ears or applications mixing music and surrounding sounds playback. Although claimed otherwise, these solutions may not be a safe alternative for conventional earphones when used in traffic. Fundamental research shows that bone conduction headphones may allow for an undisturbed detection of car sounds in the near proximity of the listener (Chang-Geun, Lee & Spencer, 2011), but this type of headphones still impaired the auditory localisation of critical environmental sounds (May & Walker, 2017). Furthermore, cyclists may misguidedly believe that using a bone conduction headphones does not impact their auditory perception, which in turn may undermine cyclists' motivation to compensate for the negative effects of listening to music.

Negative effects on auditory localisation of traffic sounds may also occur when a cyclist is listening to music through one earphone only. This way of listening to music is often considered safer than using two earphones since traffic sound can still reach one ear. As shown by de Waard, Edlinger & Brookhuis (2011) listening to music through one earphone does not impair detection of traffic sounds. However, cyclists' auditory localisation may suffer since for correct localisation of sounds in space output of both ears is needed. Listening to music through one earphone may therefore yet pose a safety hazard for cyclists.

With regard to electric cars, adding artificial sound is often proposed as a solution for the problem of low sound intensity of these cars. Some initiatives have already been taken. The European Parliament decided in 2014 that, starting in July 2019, all new electric vehicles will be equipped with an acoustic vehicle alerting system (AVAS) (European Commission, 2014). Likewise, the US Department of Transportation's National Highway Traffic Safety Administration (NHTSA) recently finalized minimum sound requirements for hybrid and electric cars driven at low speeds (up to 30 km/h) (NHTSA, 2018). The requirements are applicable beginning on September 1, 2020.

Add-on sound cannot, however, be considered a solution for the low sound emission of electric cars in all traffic situations. Research shows that add-on sound may improve detectability of slow-moving electric cars in low ambient sounds levels. In high ambient sound, however, the detection of electric cars with add-on sound is still impaired (Poveda-Martínez et al., 2017). Furthermore, to be effective in higher ambient sound levels noise, the sound intensity of artificial sound would have to be quite high and thus unacceptable in urban situations (Yamauchi et al., 2010). Interestingly, it has been estimated that replacing all cars with electric ones would reduce the overall sound level in urban areas up to 3-4 dB (Campello-Vicente et al., 2017; Kaliski, Old & Blomberg, 2012; Verheijen & Jabben, 2010). If all electric cars were equipped with artificial sound and driven at 30 km/h, the reduction of the overall sound level will be rather small (by 1 dB at 30 km/h).

Another argument against add-on sound is that it can have a negative effect on car drivers. In the presence of artificial sound, drivers of electric cars may think that their presence can easily detected by cyclists and pedestrians and they may therefore drive less carefully than they would without the added sound (Sandberg, Goubert & Mioduszewski, 2010). Given the fact that add-on sound does not seem to be effective in all traffic situations, less careful driving and lack of compensatory behaviour among drivers of electric cars may lead to risky situations for cyclists and pedestrians.

Besides the above mentioned road safety perspective, there is also an environmental argument against add-on sounds. From the environmental point of view, quiet cars are highly valuable as they can contribute to noise reduction in urban environments. With the introduction of artificial warning sounds the positive effect of noise reduction will be (partly) wiped out.

6.4. Limitations and future research

6.4.1. Methodological limitations

The empirical studies presented in this thesis applied three different research methods. *Chapter 3* employed a laboratory study, *Chapter 4* an Internet survey and *Chapter 5* a semi-naturalistic study in real traffic. Each of these research methods has limitations, which were discussed in the respective chapters. This section briefly summarises and supplements these limitations and provides recommendations for future studies.

A laboratory setting was used in this thesis to study localisation of electric and conventional cars. The reasons for choice of this method, which are in detail discussed in *Section 3.1.2*, were mainly related to the need for experimental control and the need to ensure safe research conditions for the participants. Although a laboratory setting better suited our research aims, this research method has also important weaknesses. Due to the high level of control, external validity of laboratory studies is reduced. Unlike the participants in the lab, cyclists are typically in motion navigating through traffic. The laboratory setting used in our study did not account for factors such as cognitive demands associated with the actual cycling, visual cues or the presence of aerodynamic noise and other environmental noises. We can expect that due to these factors, auditory localisation of cars during the actual cycling is more difficult than in a lab. To illustrate aerodynamic noise caused by the head displacement through the air, increases with the increasing speed and at low frequencies it can reach 51-66 dB at 13km/h and 57-72 dB at 23 km/h. Similarly, auditory detection of cars is likely to be more challenging for cyclists than for static pedestrians who participated in the detection studies presented in the literature review (*Chapter 2*).

Another weakness of a laboratory setting is that auditory perception of sounds in a lab may differ from the perception of sounds in real traffic. It is not easy to exactly reproduce a sound field in a lab, including all spatial cues used for auditory perception (e.g. reverberation, HRTFs, ITD and ILD) as they would occur in a natural setting. Therefore the auditory perception of car sounds in a laboratory setting may differ from how car sounds are perceived in real traffic. To illustrate, a recent study in which pedestrians assessed the sounds of electric vehicles showed that detection distances in the virtual world were larger (the vehicles were earlier detected) than detection distances in the real world (Singh et al., 2015). Additionally, the sounds were more 'recognisable as a vehicle' in the real world than in the virtual-world. The same study showed, however, that for both detection distance and recognisability the virtual setting correctly predicted the ranked order of car sounds. Lab studies may therefore be more appropriate to investigate relative differences between various factors and conditions influencing cyclists' auditory perception, rather than to provide normative data. Therefore future studies wishing to relate the time from first detection of a target car to the time needed to perform a specific cycling manoeuvre should be performed during actual cycling.

Self-reported data was used in this thesis to study a relationship between the frequency of listening to music and conversing on the phone on the one hand and incidents on the hand using. The *Internet survey* presented in *Chapter 5* allowed us to collect a broad range of data from a large number of respondents. Surveys are especially helpful for investigating constructs that are impossible or infeasible to observe: such as mental processes, attitudes or opinions, but also one's involvement in crashes, which are very rare events. As already mentioned in *Section 5.4.2* surveys rely on accuracy of memory and honesty of reporting and may reflect what people think they do, rather than their actual behaviour. Research shows, for example, that discrepancies exist between the frequency of self-reported and actual smartphone use (see e.g. Abeelee, Beullens & Roe, 2013), especially when the precise number of uses needs to be estimated (Boase & Ling, 2013). Using categorical self-report response options (e.g. more than 10 times a day, 5–10 times a day, 2–4 times a day, at least once a day, 3–6 times a week, 1–2 times a week, less often, never) apparently improved performance but there was only a moderate correlation between self-reported and actual smartphone use (Boase & Ling, 2013). Although the categories used in *Chapter 5* were rather broad, respondents may also have been biased when estimating the frequency of listening to music or conversing on the phone. Unfortunately, we found no studies comparing the frequency of self-reported and actual smartphone use while in traffic.

Furthermore, cyclists' crash and incident estimations may have been prone to recall problems. Recent crashes are more likely to be reported than older ones and injury crashes are more likely to be reported than non-injury crashes. A study of Cannell, Marquis & Laurent (1977) shows that almost all crashes which occurred within the previous three months were reported (99% of injury crashes and 94% of non-injury crashes), while only 63% of non-injury crashes and 78% of injury crashes which occurred within the previous 9-12 months were reported. Due to the limited number of crashes reported in *Chapter 5*, incidents were used to analyse the impact of listening to music and talking on the phone on cycling safety. Since cyclists were asked to report incidents that had occurred in the previous month recall problems may have been minimized. On the other hand, as incidents are typically less serious and thus less easily memorable than crashes, some incidents may have remained unreported.

To overcome the disadvantages of using self-reported data, we recommend collection of objective data to study the crash risk of cyclists listening to music or conversing on the phone. For example, a naturalistic methodology could be

applied to observe cyclists in their natural setting using various instruments (sensors and cameras) that unobtrusively register vehicle manoeuvres, cycling behaviour and external conditions (see more about NC method Dozza & Werneke, 2014; Johnson et al., 2010). Since crashes are rare events, applying naturalistic methodology to study crash risk requires a long period of data collection and advanced infrastructure to process the large amounts of data. Analysing naturalistic data is extremely time-consuming. Therefore the use of this method to estimate cyclist crash risk was beyond the scope of this thesis.

A fully naturalistic study could not be performed, however, a semi-naturalistic approach was used in the study presented in *Chapter 5* to examine bicyclists' glance behaviour at uncontrolled intersections. Glance behaviour in this study was recorded with an *eye-tracker*. The use of an eye-tracker is not without limitations. As mentioned in *Chapter 5* eye-trackers measure where a person's fovea is directed. Foveal input is used by human visual system for object identification, hazard perception and conscious awareness (see e.g. Castro, 2009). Given the nature of eye-tracking technology, the study has not taken into account the role of peripheral vision. Peripheral vision plays an important role in spatial localisation, guidance of locomotion and maintaining balance while cycling. Peripheral vision is very sensitive to contrast and motion and serves as an early warning system for moving targets entering the visual field (see e.g. Duchowski, 2003). It is possible that even if a cyclist's fovea is not directed to an approaching car in visual periphery, the car, due its visual features, would still capture the visual attention of the cyclist. Given the importance of peripheral vision, future studies may explore its role in detection of approaching cars.

6.4.2. Dutch setting

It is important to stress that the empirical research presented in *Chapter 3, 4* and *5* concerns Dutch setting. The Netherlands is known for its safe and extensive network of bicycle facilities and high numbers of cyclists. A safe infrastructure protects cyclist from getting involved in a crash and may to some extent mitigate performance decrements resulting from the use of a mobile phone. Furthermore the behaviour of cyclists in the Netherlands may differ from cyclists in other countries, where cycling is less popular. As shown in the study of Chataway et al. (2014) cyclists in established cycling cities reported less fear of traffic and more frequent use of the mobile phone (and cycling intoxicated) than cyclists in emerging cycling cities. Thus the use of mobile phones may be higher in the Netherlands than in countries where cycling is less popular. Furthermore, in countries with high cycling levels,

cyclists may also be used to the presence of other 'silent' road users (mainly other cyclists) and therefore rely less on auditory perception to get information about approaching traffic. Given the specificity of the Dutch setting, which may to some extent limit generalizability of the results, it is important to study cyclists' use of auditory cues among groups in which cycling is less popular or in countries with less extensive cycling infrastructure.

6.4.3. Visual-auditory interactions

Although this thesis studied cyclists' auditory perception in isolation to other sensory modalities²⁷, we realize that strong interactions exist between our auditory and visual systems. In the last two decades, audio-visual interactions have been a research topic of many fundamental studies. Auditory information has been found to facilitate the identification, detection and localisation of objects and events in the external world. Sounds, in particular looming sounds, have also been found to facilitate visual orientation towards the sound source. Looming sounds, i.e. sounds with rapidly increasing amplitude such as the sound of a car approaching, are particularly salient as they may indicate a potential threat (Leo et al., 2011).

On the other hand, studies into cross-modal attention show that inputs from the two sensory modalities may interfere with each other. Fundamental research shows that auditory tasks, especially demanding ones, reduce the useful field of view (Wood et al., 2006). Visual attention is no longer captured by abrupt visual stimuli when a concurrent auditory task is present (Boot, Brockmole & Simons, 2005).

The opposite is also true: engagement in a visual task can affect auditory perception. Performance of a perceptually demanding visual task was associated with a reduced detection of irrelevant tones (see e.g. Macdonald & Lavie, 2011). There are, however, indications that this 'inattentional deafness' is reduced when relevant auditory information is presented (Scheer, Bulthoff & Chuang, 2018).

A common feature of fundamental studies in this area is that they use irrelevant pure tones. To our knowledge, only a few studies have investigated whether the audiovisual interactions translate to traffic settings, where meaningful environmental sounds are present. Results of these studies seem to support the findings of fundamental studies. To illustrate, drivers'

²⁷ Sensory modality refers to a sensory system such as vision, hearing, smell, taste, and touch.

awareness for objects (such as billboards, other vehicles, but also unexpected objects) around them was in that study markedly diminished under high auditory load (i.e. when listening to traffic updates on a specific road) (Murphy & Greene, 2017). It would be interesting to explore to what extent visual-auditory interactions translate to cycling. To our knowledge, no studies into this area have been performed among cyclists yet. Future studies could, for example, explore how listening to music or talking on the phone while cycling impacts orienting of visual attention towards approaching vehicles as well as their localisation in space.

6.4.4. Crash involvement of electric cars

Electric cars are sometimes called ‘silent killers’ in the news, implying that the low sound emission of these cars increases the risk of crashes involving cyclists and pedestrian. However, up until now there is no evidence for such a claim. It may be possible to determine whether the risk of getting involved in a crash with cyclists or pedestrians is higher for electric cars than for conventional cars, provided detailed exposure data (i.e. kilometres travelled in urban areas) and crash data involving cyclists and pedestrians for the two types of cars is collected (for more details see also *Section 2.5.5*). It is necessary to take the exposure data into account as electric cars, due to their lower operational range, may drive more kilometres in urban areas where the probability of encountering cyclists and pedestrians is higher. Furthermore, the analysis should exclude hybrid electric cars, as it cannot be determined whether or not these cars were driven in the electric mode at the time of the crash. Except for operating in electric mode hybrid electric cars can also use petrol or diesel engines.

6.5. Conclusions

The use of a mobile phone among cyclists as well as the number of electric cars on the road are on the increase. These two trends have recently raised concerns about the use of auditory cues by cyclists (and pedestrians). Auditory cues may provide important information for cyclists about approaching vehicles, especially in situations in which visual information is less available. Therefore removing auditory cues might pose a safety hazard for cyclists. The research presented in this thesis showed that listening to music or conversing on the phone while cycling as well as the low sound emission of slow-moving electric cars indeed make use of auditory cues is challenging for cyclists. Teenage and older cyclists are particularly a concern: the former due to their frequent

engagement in secondary tasks, mainly listening to music, the latter due problems with auditory localisation of cars in motion.

Surprisingly, we found that listening to music or conversing on the phone was not associated with a higher risk of getting involved in a potentially risky traffic situation. This finding may indicate that cyclists and other road users compensate for the reduction of auditory cues. The results presented in this thesis show that cyclist and drivers of electric cars, at least to some extent, adapt their behaviour to compensate for the limited auditory input. Whether these compensatory strategies are sufficient to protect cyclists remains, however, unknown. Unfortunately, there are, to our knowledge, no studies available into whether restricted auditory perception of cyclists increases the risk of getting involved in a crash.

It cannot be ruled out that the increase of the number of electric cars in the future, will lead to other compensatory strategies than those applied now. Drivers of electric cars may get less concerned about the acoustic output of their cars in the future as the cars will be equipped with acoustic alerting system. Furthermore, when a majority of cars on the road is electric, cyclists may possibly learn to rely less on auditory information and to increase their visual attention. However, transition periods may still be potentially risky for cyclists, as they will have to cope with a mix of vehicles characterized by various acoustic properties. Therefore it is important to monitor future developments regarding the trends for electric cars and cyclists' use of mobile phones and their relation to cycling safety.

This research has broadened the limited knowledge about the use of auditory perception in cycling. Auditory perception can provide important information for cyclists about the presence and location of approaching traffic and help orient cyclists' visual attention towards the relevant sound sources. As shown in *Section 6.4*, many questions about cyclists' use of auditory cues still remain unanswered. Hopefully future studies will attempt to further explore this area and other research areas to achieve the ultimate goal of making cycling safe and sound.

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Appendix 1. Details of the studies included in the literature review

Author (date)	Study type	Location
<i>Details of studies into the use of devices with cyclists</i>		
De Waard et al. (2011)	Field experiment	The Netherlands
De Waard et al. (2010)	Field experiment, observation and survey	The Netherlands
De Waard et al. (2014)	Field experiment	The Netherlands
Goldenbeld et al. (2010)	Survey	The Netherlands
Terzano (2013)	Observation	The Netherlands
Ichikawa and Nakahara (2008)	Survey	Japan
<i>Details of studies into the use of devices with pedestrians</i>		
Walker et al. (2012)	Observation	USA
Hyman et al. (2010)	Observation	USA
Nasar et al. (2008)	Field experiment	USA
Neider et al. (2010)	Experiment in virtual environment	USA
Schwebel et al. (2012)	Experiment in virtual environment	USA
Nasar and Troyer (2013)	Crash study	USA
Stavrinos et al. (2011)	Experiment in virtual environment	USA
Hatfield and Murphy(2007)	Observation	Australia
Thompson et al. (2013)	Observation	USA
Neider et al. (2011)	Experiment in virtual environment	USA
<i>Details of studies into detectability and localisation of (hybrid) electric and conventional cars</i>		
JASIC (2009)	Acoustic measurements, laboratory study with sighted participants	Japan
Garay-Vega et al. (2010)	Acoustic measurements laboratory study with visually impaired participants	USA
Wiener et al. (2006)	Acoustic measurements field experiment with visually impaired participants	USA

Author (date)	Study type	Location
Wall Emerson et al. (2011)	Field experiment with visually impaired and sighted participants	USA
Kim et al. (2012a)	Acoustic measurements and field experiment with visually impaired participants	USA
Kim et al. (2012b)	Field experiment with visually impaired participants	USA
Wall Emerson and Sauerburger (2008)	Field experiment with visually impaired participants	USA
Mendonça et al. (2013)	Laboratory study with sighted participants	Portugal
Hong et al. (2013)	Field experiment with sighted participants	Korea
Barton et al. (2012)	Laboratory study with sighted participants	USA
Barton et al. (2013)	Laboratory study with sighted participants	USA
<i>Details of studies into safety of electric cars</i>		
Hanna (2009)	Crash study	USA
Wu et al. (2011)	Crash study	USA
Morgan et al. (2011)	Crash study	UK
Cocron et al. (2011)	Field experiment	Germany
Cocron and Krems (2013)	Field experiment	Germany
Labeye et al. (2011)	Field experiment	France

Appendix 2. (Hybrid) electric cars in pedestrian and bicyclist crashes

(Hybrid) electric cars in pedestrian and bicyclist crashes compared to the share of (hybrid) electric cars in Dutch fleet in the period 2007-2012.

	Year					
	2007	2008	2009	2010	2011	2012
% road crashes ²⁸	0.08	0.19	0.43	0.35	0.60	1.43
% of Dutch fleet comprising (hybrid) electric cars	0.15	0.31	0.52	0.72	0.89	1.15

Source: DVS (Centre for Transport and Navigation)-BRON (The national road crash register); RDW Technology and information Centre

²⁸ Percentage of crashes where a (hybrid) electric car had a collision with a pedestrian or bicyclist out of the total number of crashes where a passenger car of any type had a collision with a pedestrian or bicyclist.

Summary

Cycling safety is a major traffic safety issue both in the Netherlands and abroad. The number of cyclist fatalities in the EU has been decreasing in recent years, however at a slower rate than those of car occupants or pedestrians. In the Netherlands, 20% of road fatalities and 63% of seriously injured crash victims in 2015 were cyclists. One of the factors negatively influencing cycling safety may be related to limitations on availability of auditory cues. Auditory cues, such as tire and engine noises can provide important information about the presence and location of approaching traffic. Cyclists may benefit from auditory cues especially when visual information is less available, for example due to low visibility or obstructed view. Recently two trends have raised concerns about the use of auditory cues by cyclists. One is the growing popularity of electronic devices, mainly mobile phones, which are used by cyclists to listen to music or to have a conversation. The other trend concerns the increasing number of (hybrid) electric cars, which are generally quieter than conventional cars. This thesis addresses the concerns regarding the two trends and focuses on the following research questions:

1. To what extent does listening to music and conversing on the phone impact cyclists' auditory perception and safety?
2. To what extent do acoustic properties of (hybrid) electric cars pose a safety hazard for cyclists?

Cyclists in three age groups are the focus of this thesis: teenagers (aged 16-18), adults (aged 30-40) and older adults (aged 65-70). The teenagers and older adults are the main focus, as these age groups are particularly vulnerable in terms of cycling safety. Teenagers and older adults are also of interest from the perspective of the auditory perception of traffic sounds: teenagers due their frequent use of electronic devices; older adults due to age-related decline in hearing abilities. Cyclists in middle adulthood (30-40 years old) have been included to serve as a reference for the other two age groups.

Chapter 2 provides an overview of the current knowledge on the use of electronic devices, mainly mobile phones, by cyclists and the acoustic characteristics of (hybrid) electric cars in relation to cycling safety. For that, both a literature review and a crash data analysis of Dutch official crash databases have been carried out. This chapter also introduces a conceptual model of the role of auditory information in cycling. It is clear from literature that listening to music and conversing on the phone while cycling negatively impacts cyclists' auditory perception and cycling performance. As for (hybrid) electric cars, the problem of their quietness in particular applies to low speeds (generally up to 15-20 km/h). Slow-moving (hybrid) electric cars are more difficult to detect than conventional cars especially in environments with moderate and high ambient noise. However, the available studies do not provide conclusive evidence that (hybrid) electric cars are more dangerous for cyclists and pedestrians in terms of crash risk than conventional cars. Furthermore, the literature review provides no objective evidence for an increased crash risk for listening to music or conversing on the phone.

Research into the crash risk of (hybrid) electric cars faces two major difficulties: the small absolute numbers of crashes involving (hybrid) electric cars and the lack of data into the kilometres travelled by (hybrid) electric cars. Crash data analysis shows that Dutch crash databases cannot be used to assess risks associated with device use while cycling or with (hybrid) electric cars colliding with pedestrians or cyclists. Neither the use of devices by cyclists nor the quietness of the car is reported as a contributory factor in crashes in Dutch crash databases. Besides providing an overview of current knowledge, *Chapter 2* also identifies several important research gaps. One research gap concerns, for example, cyclists' auditory perception of car sounds. This chapter ends with a few implications of the main findings.

Chapter 3 investigates auditory localisation of conventional and electric cars among teenagers, adults and older adults. Participants in a laboratory (an acoustically treated room) were presented with a variety of vehicle motion paths relevant for cycling. The stimuli comprised sounds from conventional and electric cars driven at three speeds in two ambient sound levels. The car speeds were typical of Dutch built-up areas, that is 15 km/h ('woonerfs': roads in residential district), 30 km/h (urban access roads) and 50 km/h (urban distributor roads). The two ambient sound levels represented a relatively quiet residential area and a moderately noisy suburban area. Overall, participants were very good at determining the location and direction of cars. On average more than 90% of the presented car sounds were accurately localised.

However, older adults exhibited lower localisation accuracy than teenage or adult participants. The poorer performance of older adults may reflect some specific hearing loss. Hearing loss was present in almost 42% of older adults in this study and it comprised a variety of types (various frequencies, degree, unilateral versus bilateral). Interestingly, almost all participants without hearing loss had high localisation scores, whilst only some participants with hearing loss were impaired on the task. The study shows, furthermore, that localisation of car sounds is influenced by a number of factors. First, cars at the lowest speed were localised less accurately than those at higher speeds. Secondly, electric cars, especially those driven at 15 km/h, elicited lower location scores than conventional cars. Thirdly, the study also shows that it is more difficult to indicate from which location the car sound was coming when it is presented directly behind the listener. Fourthly, car sounds in higher ambient sound level were localised less accurately than cars in lower ambient sound level. Lastly, the location of approaching cars was less often correctly determined than that of receding cars. This last result is unexpected as approaching (looming) sounds in fundamental studies have been found to receive a 'perceptual priority' over receding sounds. Although the localisation differences presented in *Chapter 3* are small, the consequences of not being able to detect and localise approaching cars in time can have severe, even fatal, consequences for a cyclist.

Chapter 4 presents the results of an Internet survey into the impact of listening to music, talking on the phone and electric cars on cyclists' auditory perception and safety. Respondents (N=2249) were cyclists in three age groups (teenage, adult and older adults). Results of the survey show that, compared to the two other age groups, teenage cyclists are the most frequent users of a mobile phone. Teenager cyclists use their mobile phones especially to listen to music: almost a quarter of cyclists in this age group reported listening to music on each trip. Older cyclists, however, rarely use a mobile phone. This Internet study showed that listening to music and conversing on the phone negatively affect the perception of sounds crucial for safe cycling. However, the impact of listening to music on cyclists' auditory perception was higher than the impact of conversing on the phone. To determine the impact of listening to music and talking on the phone on cycling safety, respondents were asked about their involvement in traffic incidents and crashes. Crashes are rare events: only 6% of the respondents reported having been involved in a bicycle crash in the previous year. This percentage was too low to allow for further statistical analysis. Therefore, involvement in incidents was chosen as an alternative indicator of cycling safety in this study. Incidents were defined as

situations in which the cyclists got startled or surprised by some other road user in the previous month. Taking into account the influence of several confounding variables, no relationship was found between the frequency of listening to music or conversing on the phone on the one hand and the frequency of incidents on other hand. Due to validation problems, this analysis could only be performed for the group of teenage cyclists. The lack of a relationship between listening to music or conversing on the phone and incidents may be due to cyclists' engagement in compensatory behaviour. Indeed, the majority of cyclists reported adapting their behaviour while listening to music or conversing on the phone. The most often reported compensatory strategy for listening to music was turning the music down or off when necessary, looking around more frequently or using one earphone instead of two. To compensate for a phone conversation the following strategies were the most popular among cyclists: decreasing cycling speed, keeping the conversations short and looking around more frequently. Listening to music or talking on the phone whilst cycling may still pose a risk for cyclists in the absence of compensatory behaviour or in a traffic environment with less extensive and less safe cycling infrastructure than the Dutch setting. As for electric cars, the majority of cyclists in this study indicated that they never or seldom encountered quiet (electric) cars. This is in line with Dutch statistics showing that at the time of data collection only about 2% of the total number of cars in the Netherlands was electric or hybrid.

As shown in *Chapter 4*, looking around more frequently is the most frequently reported compensatory strategy among teenage cyclists. *Chapter 5* presents a study in real traffic in which objective, semi-naturalistic data is used to explore whether and to what extent teenage cyclists' glance behaviour is affected by listening to music. To this end, cyclists' eye movements were recorded by a head-mounted eye-tracker during two of their regular trips in urban environments. During one of the trips, cyclists were listening to music and during the other trip they were 'just' cycling. The study focused specifically on the glances to the right at uncontrolled intersections. At uncontrolled intersections cyclists should give way to traffic approaching from the right, according to the general rule applying in the Netherlands. Overall results show that cyclists' visual behaviour at uncontrolled intersections was not affected by listening to music. Descriptive analysis suggested that 21–36% of the participants increased their visual performance while listening to music and 43–64% decreased their visual performance in the music condition. This study also demonstrates ethical dilemmas related to performing research in real traffic. Surprisingly, no standard ethical codes exist for road safety

research. Since research in real traffic may pose a risk for participants, it is of primary importance that researchers protect cyclists participating in such a study. To protect the participants in this study a number of ethical considerations were taken into account. The most far-reaching consequence of adopting ethical considerations in this study was the termination of the data collection after fourteen cyclists had participated. The analysis based on fourteen participants revealed no visual compensation for listening to music and therefore the data collection was stopped. The target number of participants was at least 20 cyclists. This study argues for the development and implementation of ethical standards within road safety research. Not only can ethical standards help minimize risks for research participants, they can also offer clear and equal opportunity for all researchers to conduct empirical studies and to have papers accepted for publication. Finally, *Chapter 5* examined to what extent the applied experimental set-up was suitable to examine bicyclists' visual behaviour in situations crucial for cycling safety. The experimental set-up turned out suitable in terms of the eye-tracker performance, but less suitable for the investigation of cyclists' behaviour in demanding traffic environment. Due to low traffic densities, the uncontrolled intersections were probably not very demanding for cyclists.

Chapter 6 consolidates the findings presented in previous chapters to answer the two research questions posed in *Chapter 1*. Furthermore, this chapter discusses the implications of the research findings presented in this thesis. The results of this thesis indicate that, from the perspective of auditory perception, listening to music is more problematic than conversing on the phone. Listening to music is more popular than conversing on the phone, especially among teenage cyclists. Additionally, the impact of listening to music on cyclists' auditory perception is higher than the impact of conversing on the phone. Listening to music through one earphone or through special bone conduction headphones (allowing for simultaneous listening to music and surrounding sounds) should not be seen as a safe option for cyclists. This type of listening to music is likely to impair the auditory localisation of traffic sounds.

Contrary to teenage cyclists, older cyclists rarely listen to music or converse on the phone. However, making use of auditory cues to detect and localise approaching cars is apparently more challenging for older cyclists than for younger cyclists. However, it is not clear what causes the decrements of auditory performance among older people. Although auditory cues can provide important information about the presence and location of

approaching traffic, relying solely on auditory cues may pose a risk for cyclists of all ages. Traffic settings with moderate or high ambient noise or with multiple approaching cars may be especially risky as the sound of an individual car may simply get masked in these settings. With regard to electric cars, in Europe and in the United States, requirements have been introduced stating that new electric cars need to be equipped with add-on sound when driven at low speeds in order to alert cyclists and pedestrians. It can, however, be argued that adding sounds to electric cars may not necessarily be effective. For example, the detection of electric cars with add-on sound in higher ambient sound levels is likely to be impaired.

Chapter 6 also discusses limitations of the research presented in this thesis and it suggests a few areas for future research. The empirical studies presented in *Chapter 3, 4* and *5* used different research methods: a laboratory study, an Internet survey and a semi-naturalistic study in real traffic. Each of these research methods has limitations. Furthermore, the three empirical studies concern the Dutch setting, which is characterized by a safe and extensive network of bicycle facilities and high numbers of cyclists. Future research may therefore investigate the use of auditory cues among cyclists in countries with low cycling densities or less extensive cycling infrastructure. Future studies could also explore how human auditory and visual systems interact during in cycling. Moreover, it is important that future studies collect adequate data necessary to calculate the crash risk of electric cars.

Samenvatting

Fietsveiligheid is een belangrijke component van verkeersveiligheid, zowel in Nederland als daarbuiten. Binnen de Europese Unie is het aantal fietsongevallen met dodelijke afloop de laatste jaren gedaald, maar minder hard dan ongevallen met dodelijke afloop voor inzittenden van auto's of voetgangers. In 2015 was 20% van het aantal verkeersdoden en 63% van de zwaargewonde slachtoffers in Nederland een fietser.

Een onderzoeksthema binnen de fietsveiligheid is de rol die geluiden spelen. Mogelijk wordt de fietsveiligheid beïnvloed door de aanwezigheid van bepaalde auditieve signalen, of juist het ontbreken ervan. Auditieve signalen, zoals banden- en motorgeluid, geven belangrijke informatie over de aanwezigheid en de locatie van naderend verkeer. Fietzers kunnen baat hebben bij auditieve signalen, vooral als hun visuele informatie beperkt is, bijvoorbeeld in het donker, bij mist, of als het zicht wordt belemmerd. In het gebruik van auditieve signalen door fietsers zijn er momenteel twee trends die mogelijk zorgwekkend zijn. De eerste trend is de groeiende populariteit van elektronische apparaten, voornamelijk mobiele telefoons, die door fietsers worden gebruikt om naar muziek te luisteren of een gesprek te voeren. De andere trend betreft het toenemend aantal (hybride) elektrische auto's, die over het algemeen stiller zijn dan conventionele auto's. Dit proefschrift gaat in op de zorgen over deze twee trends aan de hand van de volgende onderzoeksvragen:

1. In hoeverre beïnvloeden het telefoneren en luisteren naar muziek de auditieve waarneming van verkeersgeluiden en de veiligheid van fietsers?
2. In hoeverre vormen akoestische eigenschappen van (hybride) elektrische auto's een veiligheidsrisico voor fietsers?

In dit proefschrift staan fietsers van drie leeftijdsgroepen centraal: tieners (16-18 jaar), volwassenen (30-40 jaar) en ouderen (65-70 jaar oud). De nadruk ligt echter op tieners en ouderen, omdat deze leeftijdsgroepen vanuit het perspectief van fietsveiligheid bijzonder kwetsbaar zijn. Tieners en ouderen

zijn ook van belang vanuit het perspectief van de auditieve waarneming van verkeersgeluiden: tieners vanwege hun frequente gebruik van elektronische apparatuur, ouderen vanwege het afnemende gehoorvermogen op hogere leeftijd. Fietsers van 30-40 jaar oud dienen als referentie voor de andere twee leeftijdsgroepen.

Hoofdstuk 2 geeft een overzicht van de huidige kennis over het gebruik van elektronische apparaten, voornamelijk mobiele telefoons, door fietsers en over de akoestische eigenschappen van (hybride) elektrische auto's in relatie tot fietsveiligheid. Het hoofdstuk is gebaseerd op een literatuurstudie en een analyse van gegevens uit de officiële Nederlandse ongevallenbestanden. Dit hoofdstuk introduceert ook een conceptueel model van de rol van auditieve informatie in fietsveiligheid. Uit literatuur blijkt duidelijk dat luisteren naar muziek en telefoneren tijdens het fietsen een negatieve invloed heeft op de auditieve waarneming en de fietsprestaties. Het literatuuroverzicht biedt echter geen objectief bewijs voor een verhoogd risico op ongevallen bij het luisteren naar muziek of het voeren van telefoongesprekken. (Hybride) elektrische auto's zijn vooral bij lage snelheden (doorgaans tot 15-20 km/uur) aanzienlijk stiller dan conventionele auto's. Dit is omdat bij lage snelheden van conventionele auto's het geluid van de motor dat van de banden overheerst, terwijl bij (hybride) elektrische auto's het motorgeluid juist vrijwel ontbreekt. Langzaam rijdende (hybride) elektrische auto's zijn daardoor moeilijker te detecteren, vooral bij matig of veel omgevingsgeluid. De beschikbare onderzoeksresultaten bieden echter geen overtuigend bewijs dat (hybride) elektrische auto's gevaarlijker zijn dan conventionele auto's voor wat betreft het risico op een ongeval met fietsers en voetgangers.

Onderzoek naar het ongevalsrisico van (hybride) elektrische auto's kent twee grote knelpunten: 1) een – in absolute getallen – klein aantal ongevallen met (hybride) elektrische auto's, en 2) een gebrek aan gegevens over het aantal kilometers gereden door (hybride) elektrische auto's. Analyse van de beschikbare gegevens laat zien dat de Nederlandse ongevallenbestanden niet kunnen worden gebruikt om risico's vast te stellen die gerelateerd zijn aan het gebruik van elektronische apparatuur tijdens het fietsen, of gerelateerd zijn aan stille (hybride) elektrische auto's die botsen met voetgangers of fietsers. Noch het gebruik van elektronische apparatuur door fietsers, noch het feit dat fietsers of voetgangers de auto niet hoorden naderen, wordt gerapporteerd als factor in de Nederlandse ongevallenbestanden. *Hoofdstuk 2* geeft niet alleen een overzicht van de huidige stand van kennis, maar wijst ook op enkele belangrijke lacunes in het beschikbare onderzoek. Een belangrijke lacune is dat

niet bekend is of fietsers in staat zijn om op basis van geluid auto's op tijd te detecteren en accuraat te lokaliseren. Het hoofdstuk eindigt met enkele implicaties van de belangrijkste bevindingen voor de verkeersveiligheid.

Hoofdstuk 3 onderzoekt hoe mensen (tieners, volwassenen en ouderen) conventionele en elektrische auto's op hun gehoor lokaliseren: de 'auditieve lokalisatie'. Deelnemers aan een laboratoriumonderzoek (in een speciale akoestische ruimte) kregen geluiden van naderende en wegrijdende auto's uit verschillende richtingen te horen. Dit waren geluiden van conventionele en elektrische auto's bij drie verschillende snelheden en bij twee verschillende niveaus van omgevingsgeluid. De gebruikte autosnelheden zijn typerend voor de Nederlandse bebouwde kom, te weten 15 km/uur (woonerven), 30 km/uur (erftoegangswegen binnen de bebouwde kom) en 50 km/uur (gebiedsontsluitingswegen binnen de bebouwde kom). De twee niveaus van omgevingsgeluid vertegenwoordigden een relatief rustige woonwijk en een matig lawaaiig gebied in een buitenwijk. Over het algemeen waren deelnemers erg goed in het bepalen van de locatie en bewegingsrichting van auto's. Gemiddeld was meer dan 90% van de gepresenteerde autogeluiden correct gelokaliseerd. Ouderen presteerden echter slechter dan tieners of volwassenen. Dit kan duiden op een specifiek type gehoorverlies. Bij bijna 42% van de oudere volwassenen in deze studie werd gehoorverlies geconstateerd van verschillende typen. Interessant is dat bijna alle deelnemers zonder gehoorverlies de locatie van de voertuigen goed konden inschatten, terwijl slechts sommige van de mensen met gehoorverlies dat minder goed konden.

De studie toont verder een aantal factoren aan die de lokalisatie van autogeluiden beïnvloeden. Ten eerste: auto's op lage snelheid worden minder nauwkeurig gelokaliseerd dan die op hogere snelheden. Ten tweede: elektrische auto's worden minder goed gelokaliseerd dan conventionele auto's, vooral bij 15 km/uur. Ten derde: lokalisatie blijkt lastiger als het geluid recht achter de luisteraar vandaan komt. Ten vierde: bij een hoger niveau van omgevingsgeluid worden autogeluiden minder nauwkeurig gelokaliseerd dan bij een lager niveau van omgevingsgeluid. Ten slotte: de locatie van naderende auto's wordt minder vaak correct bepaald dan die van wegrijdende auto's. Dit laatste resultaat is onverwacht, aangezien eerder onderzoek heeft aangetoond dat mensen gevoeliger zijn voor naderende geluiden dan voor verwijderende geluiden. De verschillen in lokalisatie van de autogeluiden blijken in dit onderzoek weliswaar klein te zijn, maar de consequenties van het niet tijdig kunnen detecteren en lokaliseren van naderende auto's kunnen ernstige, zelfs fatale gevolgen hebben voor een fietser.

Hoofdstuk 4 doet verslag van een internetenquête naar de impact van luisteren naar muziek, praten via de telefoon, en de aanwezigheid van elektrische auto's op de auditieve waarneming in het verkeer en de veiligheid van fietsers. Respondenten (N = 2249) waren fietsers in drie leeftijdsgroepen (tieners, volwassenen en ouderen). Uit de resultaten van het onderzoek blijkt dat tieners, vergeleken met de twee andere leeftijdsgroepen, het vaakst al fietsend een mobiele telefoon gebruiken. Tieners gebruiken hun mobiele telefoons vooral om naar muziek te luisteren: bijna een kwart van deze jonge fietsers rapporteerde tijdens elke rit naar muziek te luisteren. Oudere fietsers gebruiken echter zelden een mobiele telefoon. Deze internetenquête geeft verder aan dat fietsers die naar muziek luisteren of telefoneren 'verkeersgeluiden die cruciaal zijn om veilig te fietsen' minder goed kunnen horen. Dit blijkt sterker het geval te zijn bij luisteren naar muziek dan bij telefoneren. Om de impact van deze activiteiten op fietsveiligheid te bepalen, werd aan respondenten gevraagd naar hun betrokkenheid bij verkeersincidenten en -ongevallen. Ongevallen zijn zeldzame gebeurtenissen: slechts 6% van de respondenten gaf aan betrokken te zijn geweest bij een fietsongeval in het voorgaande jaar. Dit percentage was te laag voor verdere statistische analyse. Daarom werd in deze studie de betrokkenheid bij incidenten gekozen als een alternatieve indicator voor fietsveiligheid. Incidenten werden gedefinieerd als situaties waarin de fietsers in de voorgaande maand werden opgeschrikt of verrast door een andere weggebruiker. Rekening houdend met de invloed van verschillende andere variabelen, is geen relatie gevonden tussen luisteren naar muziek of telefoneren en het aantal gerapporteerde incidenten. Deze analyse kon alleen worden uitgevoerd voor de groep tieners. Het ontbreken van een relatie tussen luisteren naar muziek of telefoneren en incidenten kan komen doordat fietsers hun gedrag aanpassen. Het merendeel van de fietsers gaf inderdaad aan dat ze hun gedrag aanpassen als ze naar muziek luisteren of aan het telefoneren zijn. De meest gerapporteerde compensatiestrategieën bij het luisteren naar muziek waren: de muziek zachter of uit zetten als dat nodig is, vaker rondkijken, of één oortelefoon gebruiken in plaats van beide. Bij het voeren van een telefoongesprek waren de volgende compensatiestrategieën het meest populair bij fietsers: de fietssnelheid verlagen, het gesprek kort houden, en vaker rondkijken. Het luisteren naar muziek of het voeren van een telefoongesprek tijdens het fietsen kan nog steeds een risico vormen voor fietsers die geen compensatiestrategieën gebruiken of in een verkeersomgeving fietsen met minder uitgebreide en minder veilige fietsinfrastructuur dan de Nederlandse. Het merendeel van de fietsers in dit onderzoek gaf aan dat ze nooit of slechts zelden stille (elektrische) auto's tegenkomen. Dit is in lijn met Nederlandse statistieken, die

aangeven dat op het moment van gegevensverzameling slechts ongeveer 2% van het totale aantal auto's in Nederland elektrisch of hybride was. Daarbij moet ook bedacht worden dat hybride auto's niet altijd op elektriciteit rijden.

Zoals vermeld in *Hoofdstuk 4* is 'vaker rondkijken' de meest gerapporteerde compensatiestrategie onder tienerfietsers. *Hoofdstuk 5* presenteert een observatiestudie die is uitgevoerd in het echte verkeer. In deze studie zijn objectieve gegevens gebruikt om te onderzoeken of en in welke mate het kijkgedrag van fietsende tieners wordt beïnvloed door het luisteren naar muziek. Daartoe werden de oogbewegingen van fietsers tijdens twee van hun reguliere fietsritten in stedelijke omgevingen geregistreerd door een eyetracker op het hoofd. Tijdens de ene rit luisterden fietsers wel naar muziek en tijdens de andere rit niet. De studie richtte zich specifiek op het kijken naar rechts bij ongeregelde kruispunten. Volgens de algemene regel in Nederland, dienen fietsers op zulke kruispunten voorrang te verlenen aan het verkeer van rechts. Over het geheel genomen, laten de resultaten zien dat het kijkgedrag van fietsers op ongeregelde kruispunten niet wordt beïnvloed door het luisteren naar muziek. Een analyse op deelnemerniveau geeft echter wel aanwijzingen voor een individueel effect: 21-36% van de deelnemers 'kijkt meer om zich heen' tijdens het luisteren naar muziek, terwijl 43-64% juist 'minder om zich heen kijkt'. Deze studie wijst ook op ethische dilemma's met betrekking tot het uitvoeren van onderzoek in het echte verkeer. Verrassend genoeg bestaat er geen standaard van ethische codes voor verkeersveiligheidsonderzoek. Aangezien onderzoek in het echte verkeer een risico kan vormen voor de deelnemers, is het van het grootste belang dat fietsers die aan dergelijke studies deelnemen, worden beschermd tegen die risico's. In deze studie is daarom rekening gehouden met een aantal ethische overwegingen. De meest vergaande consequentie daarvan vormde het stopzetten van de gegevensverzameling nadat veertien fietsers aan het onderzoek hadden deelgenomen. De analyse op basis van de gegevens van deze veertien deelnemers bracht namelijk géén 'visuele compensatie' voor het luisteren naar muziek aan het licht: ze gingen niet 'méér' om zich heen kijken. Vanwege het risico dat daarmee gepaard gaat, werd de gegevensverzameling gestopt. Het beoogde aantal deelnemers was minimaal 20 fietsers. Deze studie pleit voor de ontwikkeling en implementatie van ethische normen binnen verkeersveiligheidsonderzoek. Niet alleen kunnen zulke ethische normen helpen de risico's voor deelnemers tot een minimum te beperken, ze kunnen ook duidelijke en gelijke kansen bieden aan onderzoekers om empirische studies uit te voeren en onderzoek geaccepteerd te krijgen voor publicatie. Tot slot geeft *Hoofdstuk 5* aan in welke mate de toegepaste experimentele opstelling

geschikt is om het kijkgedrag van fietsers te onderzoeken in situaties die cruciaal zijn voor de veiligheid van fietsers. De verzamelde eyetrackergegevens blijken van goede kwaliteit te zijn om het kijkgedrag te beoordelen. De experimentele opzet blijkt echter minder geschikt voor onderzoek naar het gedrag van fietsers in complexe verkeersomstandigheden. Vanwege de lage verkeersdichtheid waren de kruispunten zonder verkeerslichten waarschijnlijk niet erg veeleisend voor fietsers.

Hoofdstuk 6 vat de bevindingen uit de voorgaande hoofdstukken samen, met als doel om de twee onderzoeksvragen te beantwoorden die in *Hoofdstuk 1* zijn gesteld. Verder bespreekt dit hoofdstuk de verkeersveiligheidsimplicaties van de resultaten uit dit onderzoek. Deze resultaten geven aan dat, vanuit het oogpunt van auditieve waarneming van verkeersgeluiden, het luisteren naar muziek problematischer is dan telefoneren. Ten eerste is luisteren naar muziek populairder dan telefoneren, vooral bij fietsende tieners. Ten tweede is de impact van het luisteren naar muziek op de auditieve waarneming van fietsers hoger dan de impact van telefoneren. Luisteren naar muziek via één oortelefoon of via speciale beengeleidingshoofdtelefoons (waarmee gelijktijdig naar muziek en omgevingsgeluiden kan worden geluisterd) moet niet worden gezien als een veilige optie voor fietsers. Een dergelijke manier van luisteren naar muziek kan er namelijk voor zorgen dat verkeersgeluiden slechter gelokaliseerd worden.

In tegenstelling tot fietsende tieners, luisteren oudere fietsers zelden naar muziek en telefoneren ze ook zelden. Voor deze leeftijdsgroep is het echter problematischer dan voor jongere fietsers om op hun gehoor – op basis van auditieve signalen – naderende auto's te detecteren en te lokaliseren. Het is niet duidelijk wat deze vermindering in auditieve prestatie bij ouderen veroorzaakt. Hoewel auditieve signalen belangrijke informatie kunnen geven over de aanwezigheid en locatie van naderend verkeer, kan het voor fietsers van alle leeftijden een risico vormen om uitsluitend te vertrouwen op auditieve signalen. Verkeerssituaties met matig of veel omgevingsgeluid of met meerdere naderende auto's kunnen bijzonder riskant zijn, omdat het geluid van een individuele auto kan worden gemaskeerd. Voor elektrische auto's zijn in Europa en de Verenigde Staten normen opgesteld waardoor nieuwe elektrische auto's bij lage snelheid extra geluid moeten produceren om fietsers en voetgangers te waarschuwen. In hoeverre toevoeging van geluid aan elektrische auto's effectief is, is nog de vraag. Het detecteren van elektrische auto's met aanvullend geluid is waarschijnlijk nog steeds lastig in een lawaaige omgeving.

Hoofdstuk 6 bespreekt ook de beperkingen van het onderzoek dat in dit proefschrift gepresenteerd is, en geeft een aantal suggesties voor toekomstig onderzoek. De empirische studies gepresenteerd in *Hoofdstuk 3, 4* en *5* gebruikten verschillende onderzoeksmethoden: een laboratoriumonderzoek, een vragenlijstonderzoek via internet en een semi-naturalistisch onderzoek in het echte verkeer. Elk van deze onderzoeksmethoden heeft beperkingen. Verder hebben de drie empirische onderzoeken betrekking op de Nederlandse situatie, gekenmerkt door een veilig en uitgebreid netwerk van fietsvoorzieningen en een groot aantal fietsers. Toekomstig onderzoek zou het gebruik van auditieve signalen onder fietsers in landen met lage fietsdichtheden of minder uitgebreide fietsinfrastructuur kunnen onderzoeken. Toekomstige studies zouden verder kunnen onderzoeken hoe auditieve en visuele informatie geïntegreerd wordt tijdens het fietsen. Bovendien is het belangrijk dat toekomstige studies voldoende gegevens verzamelen om het ongevalsrisico van elektrische auto's te kunnen berekenen.

Streszczenie

Bezpieczeństwo rowerzystów jest jednym z głównych problemów bezpieczeństwa ruchu drogowego zarówno w Holandii, jak i za granicą. W ostatnich latach w krajach Unii Europejskiej zaobserwowano spadek liczby ofiar śmiertelnych wśród rowerzystów, jednak spadek ten jest mniejszy niż w przypadku pieszych czy też kierowców samochodów osobowych i ich pasażerów. W 2015 roku w Holandii rowerzyści stanowili 20% ogółu ofiar śmiertelnych w wypadkach drogowych i 63% ogółu ciężko rannych ofiar wypadków. Jednym z czynników negatywnie wpływających na bezpieczeństwo rowerzystów może być ograniczona dostępność sygnałów dźwiękowych. Sygnały dźwiękowe, takie jak hałas silnika czy opon po nawierzchni, mogą dostarczyć rowerzystom ważnych informacji o obecności i lokacji nadjeżdżających pojazdów, zwłaszcza w sytuacjach, w których informacje wzrokowe są mniej dostępne. Ostatnio obawy co do korzystania przez rowerzystów z sygnałów dźwiękowych wzbudziły dwa trendy. Pierwszy dotyczy rosnącej popularności urządzeń elektronicznych, głównie telefonów komórkowych, używanych przez rowerzystów do słuchania muzyki lub prowadzenia rozmów. Drugi trend dotyczy rosnącej liczby samochodów hybrydowych i elektrycznych, które generalnie są bardziej ciche niż samochody konwencjonalne. Przedstawiona praca odnosi się do obaw związanych z tymi dwoma trendami i zawiera następujące pytania badawcze:

1. W jakim stopniu słuchanie muzyki i rozmowa przez telefon wpływa na percepcję słuchową i bezpieczeństwo rowerzystów?
2. W jakim stopniu poziom hałasu samochodów emitowany przez samochody elektryczne i hybrydowe stanowi zagrożenie dla rowerzystów?

Na potrzeby niniejszej pracy badaniem objęto rowerzystów w trzech grupach wiekowych: 16 - 18 lat, 30 - 40 i 65 - 70 lat. Najmłodsza i najstarsza grupa były grupami celowymi, ponieważ rowerzyści w wieku nastoletnim oraz ci w starszym wieku są szczególnie narażeni na niebezpieczeństwo. Poza tym, można przyjąć, że dla rowerzystów w tych grupach wiekowych, dostępność sygnałów dźwiękowych jest niższa: w przypadku nastoletnich rowerzystów z

powodu częstego korzystania z urządzeń elektronicznych a w przydatku rowerzystów w starszym wieku ze względu na pogłębiający się z wiekiem niedosłuch. Rowerzyści w średnim wieku (30-40 lat) stanowili grupę odniesienia dla pozostałych dwóch grup wiekowych.

Rozdział 2 zawiera przegląd aktualnej wiedzy na temat: 1) korzystania przez rowerzystów z urządzeń elektronicznych, głównie telefonów komórkowych, oraz 2) hałasu emitowanego przez samochody elektryczne i hybrydowe, w odniesieniu do bezpieczeństwa rowerzystów. W tym celu przeprowadzony został przegląd literatury i analiza danych pochodzących z oficjalnych holenderskich baz danych wypadków drogowych. Rozdział ten przedstawia również model konceptualny roli informacji dźwiękowej podczas jazdy na rowerze. Z przeglądu literatury wynika, że słuchanie muzyki i rozmawianie przez telefon podczas jazdy na rowerze ma negatywny wpływ na percepcję słuchową rowerzystów, jak i na samą jazdę. Jeśli chodzi o samochody elektryczne i hybrydowe, niski poziomu hałasu emitowany przez te pojazdy dotyczy w szczególności niskich prędkości (do 15-20 km/h).

Samochody elektryczne czy hybrydowe jadące z niską prędkością są trudniejsze do wykrycia niż samochody konwencjonalne, szczególnie przy umiarkowanym lub wysokim poziomie hałasu otoczenia. Jednak przegląd literatury nie dostarcza żadnych obiektywnych dowodów na to, że słuchanie muzyki lub rozmawianie przez telefon podczas jazdy na rowerze zwiększa ryzyko zaistnienia wypadku drogowego. Ponadto dostępne badania nie dostarczają jednoznacznych dowodów na to, jakoby samochody elektryczne czy hybrydowe bardziej zagrażały rowerzystom i pieszym pod względem ryzyka zaistnienia wypadku niż samochody konwencjonalne.

Badania zajmujące się powyższą kwestią napotykać na dwie główne trudności. Pierwsza z nich to niska całkowita liczba wypadków z udziałem samochodów elektrycznych i hybrydowych, a druga to brak danych odnośnie liczby kilometrów przejechanych przez samochody elektryczne i hybrydowe. Analiza holenderskich baz danych wypadków drogowych pokazuje, iż nie można ich wykorzystać do oceny ryzyka związanego z korzystaniem z telefonów komórkowych podczas jazdy na rowerze. Holenderskich baz danych wypadków drogowych nie można również użyć do oceny ryzyka zaistnienia wypadku z udziałem samochodu o napędzie elektrycznym oraz rowerzysty (albo pieszego). Ani korzystanie z telefonów komórkowych przez rowerzystów, ani niski poziom hałasu samochodu nie są rejestrowane jako czynniki przyczyniające się do wypadków. Oprócz przeglądu aktualnej

wiedzy, *Rozdział 2* pokazuje również kilka ważnych luk badawczych. Jedną z tych luk dotyczy na przykład postrzegania dźwięków samochodów. *Rozdział* kończy się kilkoma implikacjami głównych rezultatów.

Rozdział 3 dotyczy lokalizacji słuchowej samochodów konwencjonalnych i elektrycznych przez nastolatków, dorosłych i osoby starsze. Uczestnicy badania zostali umieszczeni w laboratorium akustycznym, gdzie słuchali nagrań dźwiękowych samochodów konwencjonalnych i elektrycznych, które nadjeżdżały i odjeżdżały w różnych kierunkach. W badaniu użyto trzech prędkości samochodów oraz dwóch poziomów hałasu otoczenia. Wybrano trzy prędkości typowe dla holenderskich obszarów zabudowanych, tj. 15 km/h (prędkość typowa dla "woonerfs" czyli stref zamieszkania), 30 km/h (prędkość typowa dla dróg dojazdowych na terenie zabudowanym) i 50 km/h (prędkość typowa dla dróg głównych na terenie zabudowanym). Użyto również dwa poziomy dźwięku otoczenia: względnie cichą strefę zamieszkania i umiarkowanie głośny obszar podmiejski. Ogólnie, uczestnicy osiągnęli wysokie wyniki jeśli chodzi o określenie pozycji i kierunku ruchu samochodów. Średnio ponad 90% prezentowanych dźwięków samochodów zostało poprawnie zlokalizowanych. Jednak osoby starsze popełniły więcej błędów niż osoby nastoletnie lub w średnim wieku. Trudność z lokalizacją słuchową zaobserwowana u osób starszych może być spowodowana pewnym typem niedosłuchu. W niniejszym badaniu, niedosłuch występował u prawie 42% osób starszych i obejmował wiele różnych typów (niedosłuch różnych częstotliwości, stopnia, jednostronny lub dwustronny). Co ciekawe, prawie wszyscy uczestnicy z dobrym słuchem uzyskali wysokie wyniki podczas lokalizacji słuchowej samochodów, podczas gdy tylko niektórzy uczestnicy z niedosłuchem mieli z problem z lokalizacją.

Badanie wykazało ponadto, że na lokalizację słuchową samochodów wpływa szereg czynników. Po pierwsze, samochody jadące z najniższą prędkością były częściej poprawnie lokalizowane niż te jadące z wyższymi prędkościami. Po drugie, poprawna lokalizacja samochodów elektrycznych, zwłaszcza jadących z prędkością 15 km/h, okazała się trudniejsza niż lokalizacja samochodów konwencjonalnych. Po trzecie, trudniej jest wskazać, skąd dobiega dźwięk samochodu, gdy dźwięk ten jest emitowany bezpośrednio za słuchaczem. Po czwarte, lokalizacja słuchowa samochodów w otoczeniu o niższym poziomie hałasu okazała się łatwiejsza niż lokalizacja w otoczeniu o wyższym poziomie hałasu. Wreszcie, trudniej jest określić, z którego miejsca nadjeżdża samochód, niż w które miejsce odjeżdża. Ten ostatni rezultat jest zaskakujący, ponieważ z badań fundamentalnych wynika, że percepcja

dźwięków zbliżających się obiektów jest traktowana priorytetowo w porównaniu z percepcją oddalających się dźwięków. Różnice w lokalizacji dźwięków samochodów wykazane w tym badaniu są niewielkie, jednak niemożność wykrycia i zlokalizowania nadjeżdżających samochodów może mieć dla rowerzysty poważne, a nawet śmiertelne konsekwencje.

W *Rozdziale 4* przedstawiono wyniki ankiety internetowej dotyczącej wpływu słuchania muzyki, prowadzenia rozmów telefonicznych i poziomu hałasu samochodów elektrycznych na percepcję słuchową rowerzystów i ich bezpieczeństwo. W badaniu wzięli udział rowerzyści (N = 2249) w trzech grupach wiekowych (osoby nastoletnie, dorosłe i starsze). Wyniki badania pokazują, że w porównaniu do dwóch pozostałych grup wiekowych, nastoletni rowerzyści najczęściej korzystają z telefonu komórkowego. Nastoletni rowerzyści używają telefonów komórkowych szczególnie do słuchania muzyki: prawie jedna czwarta rowerzystów w tej grupie wiekowej zadeklarowała, że słucha muzyki podczas każdej przejażdżki. Rowerzyści w starszym wieku rzadko korzystają z telefonu komórkowego. Niniejsza ankieta wykazała, że słuchanie muzyki i rozmawianie przez telefon negatywnie wpływa na percepcję dźwięków kluczowych dla bezpiecznej jazdy na rowerze. Jednak negatywny wpływ słuchania muzyki na percepcję słuchową rowerzystów był większy niż wpływ rozmowy telefonicznej.

Aby określić wpływ słuchania muzyki i rozmowy telefonicznej na bezpieczeństwo rowerzystów, respondenci zostali zapytani o udział w incydentach i wypadkach. Wypadki zdarzają się relatywnie rzadko: tylko 6% respondentów zadeklarowało, że w poprzednim roku uczestniczyło w wypadku rowerowym. Odsetek ten był zbyt niski, aby mógł zostać użyty do dalszej analizy statystycznej. Dlatego też do analizy użyto innego wskaźnika bezpieczeństwa, jakim jest uczestnictwo w incydentach podczas jazdy na rowerze w przeciągu poprzedniego miesiąca. Incydenty zostały zdefiniowane jako sytuacje, w których rowerzyści przestraszyli się innego użytkownika drogi lub zostali przez niego zaskoczeni. Po uwzględnieniu w analizie kilku zmiennych zakłócających, nie znaleziono związku między częstotliwością słuchania muzyki lub prowadzenia rozmowy przez telefon a częstotliwością incydentów. Analiza ta została przeprowadzona jedynie dla grupy nastoletnich rowerzystów, z uwagi na problemy z walidacją danych osób dorosłych i starszych. Brak związku między słuchaniem muzyki lub rozmową przez telefon a incydentami może być spowodowany zachowaniami kompensacyjnymi rowerzystów. Rzeczywiście, większość rowerzystów zadeklarowała, że zmienia swoje zachowanie na drodze podczas słuchania

muzyki lub rozmowy telefonicznej. Najczęściej deklarowanymi strategiami kompensacyjnymi podczas słuchania muzyki było wyłączenie lub ściszenie muzyki, częstsze rozglądanie się lub używanie jednej słuchawki zamiast dwóch. Za to najbardziej popularnymi strategiami kompensacyjnymi podczas rozmowy telefonicznej okazały się: zmniejszenie prędkości, skrócenie czasu rozmowy i częstsze rozglądanie się. Słuchanie muzyki lub rozmowa przez telefon podczas jazdy na rowerze może nadal stwarzać ryzyko dla rowerzystów w przypadku braku zachowań kompensacyjnych lub w miejscach, gdzie infrastruktura rowerowa jest mniej rozbudowana i mniej bezpieczna niż ta w Holandii. Jeśli chodzi o samochody elektryczne, większość rowerzystów w tym badaniu zadeklarowała, że nigdy, bądź rzadko napotyka ciche samochody (elektryczne). Jest to zgodne z holenderskimi statystykami pokazującymi, że w czasie gromadzenia danych do tego badania tylko około 2% całkowitej liczby samochodów w Holandii stanowiły samochody elektryczne lub hybrydowe.

Jak pokazano w *Rozdziale 4*, częstsze rozglądanie się było najczęściej deklarowaną strategią kompensacyjną wśród nastoletnich rowerzystów. *Rozdział 5*, przedstawia badanie w warunkach rzeczywistego ruchu drogowego, w którym obiektywne, seminaturalne dane zostały wykorzystywane do zbadania, czy i w jakim stopniu słuchanie muzyki wpływa na aktywność wzrokową nastoletnich rowerzystów. W tym celu ruchy gałek ocznych rowerzystów zostały zarejestrowane podczas dwóch regularnych przejazdów po mieście. Do pomiaru ruchów gałek ocznych użyto okulografu zamontowanego na głowie rowerzysty. Podczas jednej z przejazdów rowerzyści słuchali muzyki, a w czasie drugiej 'tylko' jechali na rowerze. Badanie w szczególności dotyczyło analizy spojrzeń rowerzystów skierowanych w prawo na skrzyżowaniach równorzędnych. Na skrzyżowaniach równorzędnych rowerzyści powinni ustąpić pierwszeństwa pojazdom nadjeżdżającym z prawej strony, zgodnie z ogólną zasadą „prawej ręki” obowiązującą w Holandii. Wyniki całościowe pokazują, że słuchanie muzyki nie miało wpływu na aktywność wzrokową rowerzystów na skrzyżowaniach równorzędnych. Statystyki opisowe wykazały jednak, że 21-36% uczestników zwiększyło swoją aktywność wzrokową podczas słuchania muzyki, a 43-64% zmniejszyło aktywność wzrokową przy muzyce. Badanie to demonstrowa również dylematy etyczne związane z prowadzeniem badań w warunkach rzeczywistego ruchu drogowego. Zdumiewa fakt, że nie istnieją żadne standardy etyczne dla badań nad bezpieczeństwem ruchu drogowego. Ponieważ badania w warunkach rzeczywistego ruchu drogowego mogą

stwarzać ryzyko dla uczestników, jest niezwykle ważne, aby badacze chronili rowerzystów biorących udział w takim badaniu.

Aby ochronić uczestników niniejszego badania, wzięto pod uwagę kilka kwestii etycznych. Najbardziej dalekosiężną z nich było przerwanie gromadzenia danych po zgromadzeniu danych czternastu rowerzystów. Analiza statystyczna oparta na danych czternastu uczestników nie wykazała wzmózonej aktywności wzrokowej podczas słuchania muzyki. Na podstawie tej analizy podjęto decyzję o przzerwaniu dalszego gromadzenia danych, gdyż uczestnictwo w badaniu mogłoby narazić kolejnych rowerzystów na niebezpieczeństwo. Docelowo planowano zgromadzić dane co najmniej 20 rowerzystów. Niniejsze badanie opowiada się za opracowaniem i wdrożeniem standardów etycznych dla badań nad bezpieczeństwem ruchu drogowego. Standardy etyczne nie tylko pomogłyby zminimalizować ryzyko dla uczestników badań, ale także zapewnić równe szanse naukowcom na przeprowadzenie badań empirycznych i ich publikację w czasopiśmie naukowych. Wreszcie *Rozdział 5* bada, w jakim stopniu zastosowana metoda eksperymentalna okazała się odpowiednia do zbadania aktywności wzrokowej rowerzystów w sytuacjach istotnych dla ich bezpieczeństwa. Metoda eksperymentalna okazała się odpowiednia pod względem jakości danych zebranych poprzez okulograf, ale mniej przydatna do zbadania zachowania rowerzystów w trudnych sytuacjach drogowych. Ze względu na małe zagęszczenie ruchu, skrzyżowania równorzędne prawdopodobnie nie stanowiły zbyt trudności dla rowerzystów.

Rozdział 6 konsoliduje wyniki badań omówionych w poprzednich rozdziałach, w celu udzielenia odpowiedzi na dwa pytania badawcze przedstawione w *Rozdziale 1*. Ponadto rozdział ten omawia implikacje wyników badań przedstawionych w niniejszej pracy. Wyniki niniejszej pracy wskazują, że z perspektywy percepcji słuchowej, słuchanie muzyki podczas jazdy na rowerze jest bardziej problematyczne niż rozmowa przez telefon. Po pierwsze, słuchanie muzyki jest bardziej popularne niż rozmawianie przez telefon, szczególnie wśród nastoletnich rowerzystów. Poza tym, negatywny wpływ słuchania muzyki na percepcję słuchową rowerzystów jest wyższy niż wpływ rozmowy telefonicznej. Słuchanie muzyki przez jedną słuchawkę lub używanie specjalnych słuchawek wykorzystujących przewodnictwo kostne (pozwalające na równoczesne słuchanie muzyki i otaczających dźwięków) nie powinno być postrzegane jako bezpieczna opcja dla rowerzystów. W przeciwieństwie do nastoletnich rowerzystów, starsi rowerzyści rzadko słuchają muzyki i rzadko rozmawiają przez telefon. Jednak, ze względu na

wysoki wskaźnik śmiertelności w wypadkach, starsi rowerzyści również stanowią powód do zmartwień.

Wyniki zaprezentowanej pracy wskazują, że wykorzystanie sygnałów dźwiękowych do wykrywania i lokalizacji zbliżających się samochodów jest trudniejsze dla tej grupy wiekowej niż dla młodszych rowerzystów. Jednak nie jest jasne, co powoduje obniżenie sprawności słuchowej u osób starszych. Chociaż sygnały dźwiękowe mogą dostarczyć ważnych informacji o obecności i lokacji zbliżających się pojazdów, poleganie wyłącznie na dźwięku może stanowić ryzyko dla rowerzystów w każdym wieku. Sytuacje drogowe z umiarkowanym lub wysokim poziomem hałasu otoczenia lub z kilkoma samochodami nadjeżdżającymi jednocześnie mogą być szczególnie ryzykowne, ponieważ w takich warunkach dźwięk pojedynczego samochodu może po prostu zostać zamaskowany.

Jeśli chodzi o samochody elektryczne, w Europie i Stanach Zjednoczonych wprowadzono wymogi, zgodnie z którymi nowe samochody elektryczne będą musiały emitować dodatkowy dźwięk przy niskich prędkościach, po to, aby ostrzec rowerzystów i pieszych. Można jednak argumentować, że wyposażenie samochodów elektrycznych w dodatkowy dźwięk niekoniecznie musi być skuteczne. Na przykład, wykrywalność samochodów elektrycznych z dodatkowym dźwiękiem przy wyższych poziomach hałasu otoczenia będzie prawdopodobnie słaba.

Rozdział 6 omawia także ograniczenia badań prezentowanych w tej pracy i przedstawia kilka propozycji dla przyszłych badań. W badaniach empirycznych przedstawionych w *Rozdziałach 3, 4 i 5* wykorzystane zostały różne metody badawcze: badanie laboratoryjne, ankieta internetowa i obserwacja w warunkach rzeczywistego ruchu drogowego. Każda z tych metod badawczych ma swoje ograniczenia. Ponadto, te trzy badania empiryczne dotyczą holenderskiej sytuacji, gdzie liczba rowerzystów jest znaczna a infrastruktura rowerowa jest rozbudowana i bezpieczna. Przyszłe badania mogą zatem dotyczyć korzystania z sygnałów dźwiękowych przez rowerzystów w krajach o niskim zagęszczeniu rowerzystów. Przyszłe badania mogłyby również uwzględnić współdziałanie systemu słuchowego i wzrokowego podczas jazdy na rowerze. Co więcej, ważne jest, aby przyszłe badania zebrały odpowiednie dane dotyczące liczby przejechanych kilometrów przez samochody elektryczne, gdyż te dane są niezbędne do obliczenia ryzyka zaistnienia wypadku z udziałem tego typu pojazdów.

Curriculum Vitae

Agnieszka Stelling-Kończak was born in Kalisz, Poland, on 23rd March, 1976. After obtaining her high school diploma at I Liceum Ogólnokształcące in Kalisz in 1995, she went to study English Language at Language Teachers' Training College in Kalisz. She graduated in 1998 with a Bachelor of Arts degree. Agnieszka continued her studies at Adam Mickiewicz University of Poznań, Poland, and graduated in 2000 with a Master of Arts degree in English Philology. During her Master's studies she also worked as a teacher of English at a secondary school in Kalisz. Having moved to the Netherlands, she worked as a teacher of English at a vocational school in Hillegom. In 2002 Agnieszka went to study Psychology at Leiden University, the Netherlands, where she obtained a Master of Science degree with distinction in (Applied) Cognitive Psychology in 2008. Upon graduation, she decided to make a career switch into the field of traffic safety research. Since 2008 she has been working as a researcher at SWOV Institute for Road Safety Research. Her main research interests cover road user distraction, road safety implications of electric cars, and the safety of riders of electric bicycles and speed pedelecs.

SWOV-Dissertatiereeks

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