

Cycling and sounds: the impact of the use of electronic devices on cycling safety

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Abstract

The role of auditory perception of traffic sounds has often been stressed, especially for vulnerable road users such as cyclists or (visually impaired) pedestrians. This often in relation to two growing trends feared to negatively affect the use of auditory signals by road users: popularity of electronic devices (e.g. mobile phones, portable music players) and the number of quiet electric cars. Notwithstanding the concerns about impact of both trends on the safety of vulnerable road users, the potential safety implications of limited auditory information available while cycling have not been systematically studied yet. This paper consolidates current knowledge about the use of electronic devices in relation to cycling safety. Based on a proposed conceptual model, the paper provides a qualitative estimation of the extent to which limited availability of auditory information (caused by the use of electronic devices) while cycling constitutes a road safety hazard. Literature analysing official and self-reported crash data and research into the effects of using electronic devices on cycling performance have been used. Results suggest that the concerns about the use of electronic devices while cycling are justified. Listening to music and talking on the phone negatively influence cycling performance and self-reported crash risk. However, it is difficult to prove that these effects are (only) due to the limited availability of auditory information.

Introduction

The role of vision and visual attention for safe management of road hazards has been the object of more extensive scientific research than has auditory processing. Nevertheless the importance of auditory perception of traffic sounds and vehicle movement for road safety has often been stressed in the last two decades, especially in relation to vulnerable road users (e.g. Ashmead et al., 2012; Pfeffer & Barneclutt, 1996), such as cyclists (Mori & Mizohata, 1995) or (the visually impaired) pedestrians (e.g. Wall Emerson et al., 2011). Cyclists and pedestrians presumably rely more on auditory cues to detect and localise other road users than car drivers do. The interest in auditory perception of traffic sounds has been generated by two growing trends feared to negatively affect the use of auditory signals by road users. One is the rising number of quiet electric and hybrid cars on the road. Global sales of electric vehicles has more than doubled between 2011 and 2012 (IEA, 2013). Many European countries want to stimulate the use of electric cars, increasing the number of electric cars profoundly in the near future. The Netherlands, for example, aims to have 200,000 electrically powered cars in 2020 and one million in 2025 (IEA, 2012). Currently (January 2013), there are more than 90.000 fully electric and hybrid cars in the Netherlands which constitute 1.1% of the total number of Dutch cars. The second trend concerns the increasing preoccupation with portable electronic media devices used by road users to

listen to music or to have a phone call. A Dutch internet survey shows that 39% of the cyclists listen to music at least occasionally and 55% of the cyclists at least occasionally engage in a phone call while cycling (Goldenbeld, Houtenbos & Ehlers, 2010; Goldenbeld et al., 2012). Speech and music are feared to reduce the availability of auditory cues from the traffic environment leading in the end to unsafe situations.

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 been carried out among (visually impaired) pedestrians focusing 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 injury represents one of major traffic safety issues. In the Netherlands, a country having excellent road safety performance and known for the extensive bicycling infrastructure and widespread use of the bicycle among the population, road safety of cyclists shows a less favourable development than that of other road users. While in the period of 2000-2009 the number of fatalities among car occupants shows a continuing decrease (SWOV, 2011), the number of fatalities among cyclists has declined only slightly and actually has not decreased since 2004 (Reurings et al., 2012). Moreover, the number of seriously injured cyclists is actually showing an increasing trend over the period 2000–2009. Data from the UK and Germany show similarities as regards an increase of seriously injured cyclists (Pastor, 2012). Considering these trends in cycling safety, it is necessary to identify and address cycling problem areas. Limited availability of auditory cues from traffic environment may form one of these areas. As electronic devices are getting more and more popular among road users and the number of (hybrid) electric cars on the road is growing, it is important to get insight into how these developments affect auditory perception of cyclists and eventually cycling safety.

Limited auditory information and cycling safety

A conceptual model can be very helpful to understand the role of auditory information in cycling safety. Numerous models of driver behaviour have been developed but most of them do not incorporate human information processing (see, e.g. Cacciabue, 2007), which auditory processing is a part of. Human information models consist of quite general stages, which include perception, decision, response selection and response execution. A specific model incorporating the impact of auditory information on traffic safety is lacking. Therefore, in this paper a conceptual model of the role of auditory information in cycling is proposed (Figure 1). 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 (e.g. Baldwin).

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) (e.g. Baldwin, 2012). Sound interpretation involves for example sound recognition, its identification and the location of the sound source in space.

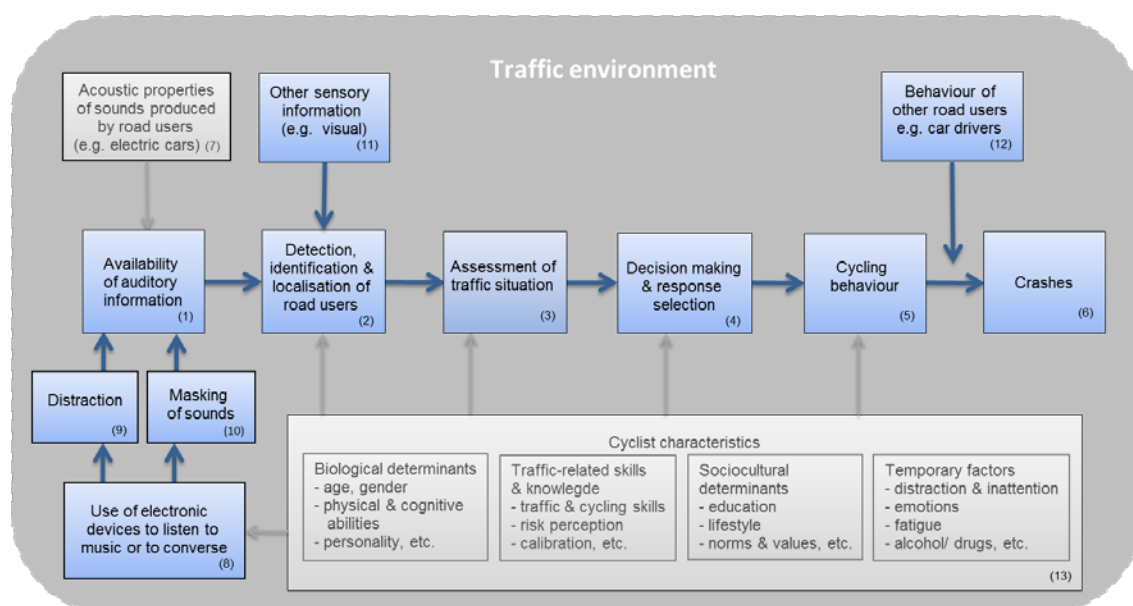


Figure 1 Model of the role of auditory information in cycling safety

For a cyclist the interpretation of a traffic sound may involve detection, identification of the sound source as certain type of road user (a car, pedestrian, motorcyclists) and localisation of the sound source in space (e.g. their location, speed, movement, direction) (2), even if it cannot be seen (11). Therefore, hearing of traffic sounds is considered to be especially important for gathering information about approaching road user from areas outside one's visual scene (e.g. coming from behind - as cyclists usually do not have a rear view mirror) (Ashmead et al., 2012; Mori & Mizohata, 1995). By means of providing information about other road users, auditory information can help cyclists to assess a traffic situation (3) and to decide which behaviour to adopt (4).

This facilitatory role of auditory information and the consequent assessment of traffic situations can be negatively affected by the use of electronic media devices while cycling (such as mobile phones or portable music players, e.g. MP3) (8) and by a low sound emission of electric cars (7). Talking on the phone and listening to music may cause auditory distraction (9) by diverting attention away from the traffic task or may simply mask the traffic sounds (10). Auditory cues used by a cyclist to detect and localise other road users can then be reduced (1). For example, when no traffic sounds are perceived, a cyclist may wrongly conclude that there are not any other road users nearby (4) and take an unsafe action (5) based on this wrong conclusion. One's assessment of a traffic situation and cycling performance based on this assessment has obviously consequences for road safety. A degraded cycling performance may give rise to crashes (6), if in the presence of traffic-related hazards, it is not compensated by the cyclist himself or other road users involved (12). For example, a car driver who is aware of the fact that his vehicle may not be heard by a cyclist may prevent a collision by actively anticipating and reacting to the actions of the cyclist at stake.

By influencing one's assessment of a traffic situation and cycling performance, auditory information can thus be expected to affect bicycle safety in the end. The bottom of the figure shows the importance of cyclist characteristics (13) influencing this

relationship. Cyclist characteristics refer to stable personal characteristics such as age, experience as a cyclist, skills, and knowledge, physical and cognitive abilities but also to temporary conditions such as fatigue or emotional state.

Many other factors, factors representing a specific traffic environment can be expected to influence the strength (some) of the relationships shown in Figure 1, such as bicycle condition, road infrastructure, weather, traffic- and road-related conditions. Given the scope of this paper, cyclist characteristics and possible other factors will not be addressed.

The aim of this paper

Despite the interest in the role of auditory perception for traffic safety, the potential safety implications of limited auditory information available while cycling have not been studied yet. This paper is aimed to fill this knowledge gap. More specifically, this paper provides a qualitative estimation of the extent to which limited availability of auditory information while cycling caused by the use of electronic devices constitute a road safety hazard. An estimation including the potential problem relating to the sound emission of electric cars is provided by Stelling-Konczak, Hagenzieker & Van Wee (in prep). The conceptual model presented in Figure 1 is used as a basis for the estimation. This model served mainly to investigate what is known and what is missing about the assumed relationships within the model. The current paper focuses on the Netherlands mainly because the great majority of literature relevant for this paper concerns the Dutch setting. The Netherlands is known for the widespread use of the bicycle: over 80% of the inhabitants own at least one bicycle, and on average a Dutch person cycles more than 800 kilometres a year (SWOV, 2009). The country has a long tradition in monitoring and evaluation of road safety. If available, also international literature is used in this paper. We restrict ourselves to literature into cyclists. There are a few studies about the use of devices among pedestrians. Research into the use of devices among car drivers is plentiful. Given the scope of this paper, the impact of listening to music or talking on the phone on car drivers will not be addressed in this paper. Studies into the use of devices in relation to pedestrian safety will be shortly mentioned in the Discussion-section.

Method

Literature search

Focusing on the relationships shown by the dark blue arrows in Figure 1 a literature search of the databases PsycARTICLES, PsycBOOKS, PsycINFO, Psychology and Behavioral Sciences Collection, PubMed, SAGE Journals Online, Science Direct, Scirus (Elsevier), SpringerLink, Swetwise and Web of Science used the following keywords:

- ‘Auditory perception’ in combination with ‘traffic/ road safety)/ cycling’
- ‘(Listening to) music’ in combination with ‘cycling’
- ‘Distraction’ in combination with ‘cycling’
- ‘Mobile/Cellular phones’ in combination with ‘cycling’

Furthermore, we searched in the categories “Distraction, Fatigue, Chronobiology, Vigilance, Workload” and “Pedestrians and Bicycles” in SafetyLit (a database of scholarly literature in the broad field of injury prevention and safety

promotion) weekly updates (starting from January 2011 to May 2013) as well as in the library catalogue at SWOV (Dutch Institute for Road Safety Research).

Research methods of the reviewed literature

Firstly, literature analysing official crash data (e.g. BRON – Dutch National Road Crash Register, Statistics Netherlands and LMR – the National Medical Registration) involving cyclists was used to obtain statistics on crashes caused by the use of devices by cyclists and subsequently to get information on whether these crashes were caused by the limited availability of auditory information.

Secondly, this paper discusses self-reported data concerning the causes of bicycle crashes. These subjective data are obtained in surveys among cyclists. Studying (official or self-reported) crash data is not always enough to assess the effect of a specific factor on road safety. This is partly because crashes are rare events, and partly because it is often difficult to attribute possible changes in crash statistics to only one specific factor excluding possible other contributing factors. Therefore, this paper reviews also studies using other measures that are assumed to be related to safe traffic decisions and thus ultimately to crashes. These measures can stem from measuring cycling behaviour (e.g. speed, reaction time, etc.), observations (e.g. number of conflicts with other road users) or be derived from questionnaires (e.g. rates of mental effort or risk perception).

Results

Research findings are structured along the relationships within the conceptual model described in the introduction.

The use of devices and crashes

Official crash records

Literature analysing official crash data involving cyclists was used to determine whether 1) the use of electronic devices can be found as a factor contributing to crashes and 2) whether those crashes have been caused by the limited availability of auditory information. The most important is Dutch crash database BRON - the National Road Crash Register which is based on police data on road crashes. Unfortunately, the registration rate of this data source has gradually declined in recent years. With regard to bicycle crashes, the registration rate of bicycle fatalities in 2009 was as low as 75%. The registration rate of seriously injured cycle casualties was in 2009 80% for cyclists involved in crashes with motor vehicles and only 4% for cyclists who had been seriously injured in crashes not involving motor vehicles, it is (Reurings et al., 2012).

That is why two other data sources are often used to account for the missing crashes, i.e. Statistics Netherlands and LMR - the National Medical Registration, which contain data from medical practitioners, hospitals and the district public prosecutor's offices. The use of various data sources is necessary for completeness, but it has a disadvantage - not the same information is available for all casualties.

None of these data sources provides information on the use of electronic devices while cycling. As the police in the Netherlands do not systematically register involvement of a particular distracting activity, such as the use of a mobile phone or a portable music device, no information on the contribution of these activities to road traffic crashes can be found in BRON. The other data sources do not provide

information on the use of electronic devices while having a bicycle crash either. Similarly, no information about the use of electronic devices has been found in the international literature analysing crash data involving cyclists. The existing crash data are not detailed enough to be able to make conclusions about the contribution of the use of devices to bicycle crashes not to mention information on whether the crashes involving the use of devices were caused due to the limited availability of auditory information.

Similarly to Dutch official crash records, no information about the use of electronic devices has been found in the international literature analysing crashes involving cyclists.

Self-reported crash involvement

In the Netherlands some information on the contribution of the use of electronic devices to self-reported crashes can be derived from two recent surveys. In a retrospective survey among 1141 cyclists (De Waard et al., 2010), who attended Accident & Emergency Department after they had had a bicycle crash, only 3 respondents (0.3%) stated that they were talking on their mobile phone at the time of the crash and 3.4 % of the respondents admitted that they had been listening to music during the crash. Furthermore, 3.1% of the respondents reported using the phone up to about 10 min before the crash. The contribution of the use of electronic devices to self-reported crashes has also been studied by another Dutch survey (Goldenbeld et al., 2012) which shows that in 4.3% of bicycle crashes involving any form of injury, mobile phone use (conversing but also text messaging and searching for information) has been reported. In 5% of the injury crashes (crashes were defined as all situations in which respondents fell from their bicycle), listening to music has been reported.

Both surveys, however, have some limitations inherent to the applied research method, such as the use of retrospective, self-reported data and the possibility of selective non-response bias. Furthermore, the results of this study do not necessarily prove a causal relation between listening to music or conversing on the phone and crashes. The crash may have occurred even if the cyclist had not been using electronic devices. Both studies suggest that nationally in 7-9% of self-reported injury crashes the use of devices may have contributed to the crash.

Providing percentages of road crashes in which the use of devices have been reported as a circumstance preceding the crash is not an accurate indicator for the impact of the use of these devices on the road safety level. The crash risk is more accurate as it also takes the exposure (often expressed in terms of distance travelled). The survey study by Goldenbeld et al. (2012) does correct for various exposure factors and it shows that the (self-reported) use of devices while cycling corresponds with the (self-reported) bicycle crashes. The risk of a crash for cyclists who used electronic devices on every trip, turns out to be higher compared with cyclists who never use devices while cycling: for teen cyclists a factor 1.6 higher and young adult cyclists a factor 1.8 higher than their respective age counterparts. For middle-aged and older adult cyclists, however, the use of portable electronic devices was not a significant predictor of bicycle crashes. For both surveys, however, a problem of generalising the results applies. The crashes included generally involved only (very) light injuries and may differ from crashes involving fatalities and seriously injured cyclists. The reported crash involvement cannot therefore be easily compared with the official crash data.

International self-reported data on the risk of using portable electronic devices while cycling are scarce. In a Japanese study among young cyclists (aged 15-18 years old) the experience of bicycle crash/near-crash while using a mobile phone (that occurred since entering high school), was significantly more prevalent (factor 6.88) among students who had used a phone while riding a bicycle in the past one month as compared to students who had not used a phone while cycling in the past month (Ichikawa & Nakahara, 2008). The authors reasoned that if phone use while cycling in the past month represents that one's phone use is frequent and habitual, phone use while cycling might have contributed to a bicycle (near-)crash. However, this study is a correlational study which does not need to imply a direct causal relationship between the use of a mobile phone and the crash rate. The students who phone while cycling may have lower safety orientation with an elevated (near-)crash risk regardless of their phone usage. Furthermore, firm conclusions cannot be drawn from this study also because it does not take into account other potentially relevant factors, such as the extent to which cyclist were exposed to hazardous traffic situations.

Based on the self-reported crash data (Dutch and Japanese) it can be concluded that the use of devices can increase the risk of getting involved in (light) injury crashes.

The use of electronic devices and cycling performance

Besides the analysis of crash data, the studies into effects of using devices on cycling performance can provide more insight into the negative consequences of listening to music and conversing on the phone when riding a bicycle. A number of studies, field experiments (De Waard, submitted; De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2010) and observations (Terzano, 2013; De Waard, 2010), have tried to estimate the effects of using portable devices on cycling performance. All of these studies were performed in the Netherlands.

The use of devices while cycling turns out to have a number of effects on cyclists. Talking on the phone has been found to reduce cycling speed (De Waard, submitted; De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2010), especially when performing a difficult phone task (De Waard et al., 2010). By reducing speed cyclists apparently compensate for the high secondary task demand.

Completing a task on the mobile phone resulted also in increased response time and brake time by 0.29 s on average (De Waard, Edlinger & Brookhuis, 2011). The increase was higher for handheld phoning as compared to hands-free phoning. Contrary to the use of mobile phone while cycling, no effects of listening to music were found on cycling speed (De Waard, Edlinger & Brookhuis, 2011; De Waard et al., 2010) or the response and brake time (De Waard, Edlinger & Brookhuis, 2011). The position on the road and the variation in the lateral position (swerving) was neither affected by conversing on the phone nor by listening to music (De Waard, submitted; De Waard et al., 2010).

An observation study by Terzano (2013) shows that cyclists who were using a cell phone engaged more frequently in unsafe behaviour than those who were not using a mobile phone. Similarly, listening to music while cycling was associated with a higher frequency of unsafe behaviour as compared to a condition with no listening to music. Behaviours deemed unsafe comprised of riding in the wrong direction in the bicycle lane, failing to slow down and look for crossing traffic, riding through the pedestrian

crosswalk or riding too slow when entering the intersection, causing crossing traffic to brake to allow the bicyclist to cross. Finally, in the study of De Waard et al. (2010), no more conflicts were observed among phoning cyclists as compared to non-phoning cyclists. Listening to music has no effect on the number of conflicts. A conflict in this study was operationalized as a situation where either the observed cyclist or another traffic participant had to change speed or course to avoid a crash. However, cyclists listening to music were found to disobey traffic rules (red-light running, impeding others) more frequently than cyclists who were not listening to music.

The use of devices and availability of auditory information

Some of these studies have tried to account for the effects of the use of devices on cyclists' auditory perception. Results show that auditory perception was compromised by both phoning and listening to music. Auditory stimuli (sounds of a bicycle bell) were more often missed when engaged in these activities. Cyclists listening to music using two earbuds (no matter whether it was moderate tempo, high tempo, moderate volume or high volume music) and cyclists talking on the phone have more often failed to hear the bicycle bell than cyclists who were not using electronic devices at all or those who were listening to music using one ear bud.

What is more, cyclists listening to high tempo music or loud music or listening to music using in-earbuds have more often missed a loud sound: horn honking at 100 dB (measured from 5 m distance). The horn was not missed by the cyclists listening to moderate tempo/volume music through one or two earbuds and by the cyclists talking on the phone (De Waard, Edlinger & Brookhuis, 2011).

To summarize, cyclists' auditory perception was not affected only when they listened to music using one earbud. Listening to moderate volume and tempo music using two (normal) earbuds compromised the perception of the bicycle bell but not the perception of the loud horn sound. High tempo music and high volume music through normal earbuds and moderate tempo and volume music through in-earbuds had negative effect on both auditory tasks. However listening to music through in-earbuds was more detrimental for the perception of the loud horn sound than other music conditions: the horn was missed by two out of three participants.

The use of devices and visual information

The effects of the use of electronic devices on visual perception have been studied by De Waard et al. (2010) and De Waard (submitted). Visual peripheral detection, operationalized as a number of noticed objects, was not influenced by listening to music (De Waard et al., 2010). The two objects to be noticed were placed on the ground: a printed traffic sign and a clock. The results concerning conversing on the phone are mixed. In two studies (De Waard, submitted; De Waard et al., 2010) fewer objects were correctly reported after having a phone conversation, especially a difficult one, as compared to cycling without telephoning. Less than 10% of the participants were able to report no more than one object correctly during a difficult conversation task (De Waard et al., 2010). However, in the study of De Waard, Edlinger & Brookhuis (2011) using the same difficult conversation task, no effect of conversing was found on the number of detected objects.

The use of devices and the assessment of traffic situation

The use of devices has also been found to influence perceived risk ratings. Cyclists perceived phoning (both handheld and hands-free) while cycling as more risky than just cycling (not using electronic devices) (De Waard, submitted; De Waard et al., 2010). The risk of a difficult phone task was rated higher than the risk of an easy task (De Waard et al., 2010). Risk rating for listening to music was also rated as more risky than cycling just cycling (De Waard et al., 2010). More risk is reported when listening to loud music compared with moderate volume, and when listening with in-earbuds compared with conventional earbuds (De Waard, Edlinger & Brookhuis, 2011). Higher ratings of experienced risk when using electronic devices might cause cyclists to behave more cautiously in traffic. The already mentioned Japanese study (Ichikawa & Nakahara, 2008) shows that a bicycle (near-)crash experienced while using a phone, was less prevalent among the students who had a higher perception of risk in phone usage while riding. Similarly, Goldenbeld, Houtenbos & Ehlers (2010) found that the lower perceived risk ratings, the more often cyclists were involved in a (self-reported) bicycle crash. However, the found correlations, although significant, were very low.

Discussion

This paper consolidated current knowledge about the use of electronic devices while cycling. The aim of the paper was to estimate the extent to which limited availability of auditory information while cycling caused by the use of electronic devices constitutes a road safety hazard. Results indicate that listening to music and talking on the phone affect cycling performance and crash risk.

Effects of device use on cycling performance and crash risk

Table 1 summarizes the effects of listening to music and phoning on cyclists. As shown in Table 1, listening to music and conversing on the phone while cycling does not influence cycling performance equally. Some aspects of cycling performance are similarly affected by both activities. Both listening to music and phoning have, for example, increased the number of unsafe behaviours but had no effect on the number of traffic conflicts. The differences between listening to music and phoning refer to some aspects of cycling behaviour which are influenced by only one activity (either listening to music or phoning). For example cycle speed and response time were influenced by phoning but not by listening to music. Furthermore, cyclists listening to music were found to disobey traffic rules more frequently than cyclists conversing on the phone.

As literature into the use of electronic devices among cyclists is rather scarce and concerns predominantly the Dutch setting, it is useful to compare the found effects with the research findings regarding pedestrians and the use of devices. Such a comparison is meaningful as pedestrians, just like cyclists (and contrary to motorized road users), are vulnerable road users who presumably also rely on auditory information to make decisions in traffic. A few international studies, show that pedestrians who are talking on the phone show similar effects to cyclists engaged in a phone call i.e. decrease in speed, increase in response time, increase in the number of missed visual objects and more frequent unsafe behaviour (Hyman et al., 2010; Nasar, Hecht & Wener, 2008; Neider et al., 2010).

Table 1 Summary of the effects of listening to music and phoning on cyclists

	listening to music	phoning
missed a bicycle bell	↑ *	↑
missed a horn honking	↑ **	-
cycle speed	-	↓
response time	-	↑
detected visual objects	-	-/↓
risk rating	↑	↑
conflicts	-	-
disobedience of traffic rules	↑	-
unsafe behaviours	↑	↑
crash risk (self-reported)	↑ (factor 1.6 - 1.8)	

↑ increase

↓ decrease

- no effect

* listening to music with one ear bud had no effect

** effect found for high volume music (89dB, 120bpm), high tempo music (74dB, 180bpm) music listened to through in-earbuds (74dB, 120 bpm)

One difference concerned the lateral position. Conversing on the phone while cycling had no effect on the lateral position of cyclists (De Waard et al., 2010); however pedestrians who were talking on the phone while traversing a square, weaved and changed direction more frequently than those who are not calling (Hyman et al., 2010). There are also similarities between cyclists and pedestrians as far as the effects of listening to music are concerned. For both types of road users Similarly to cyclists listening to music does not affect pedestrian speed, lateral position, response time and the number of detected visual objects (Hyman et al., 2010; Neider et al., 2010). Some differences regarding conflicts and unsafe behaviours have been found between cyclists and pedestrians. In an observation study pedestrians who were listening to music did not display a higher rate of unsafe behaviour than those not listening to music (Nasar, Hecht & Wener, 2008). However, pedestrians listening to music were more likely to be hit by a vehicle in the virtual pedestrian environment than were undistracted participants (Schwebel et al., 2012). As far as cyclists are concerned, listening to music had no effect on the number of the observed conflicts but it affected negatively the rate of unsafe behaviour. An interesting aspect of road user behaviour investigated among pedestrians but not among cyclists is looking behaviour. An observation study of pedestrians who are listening to music and conversing on the phone show no decrease in the cautionary looking behaviour (head turns) before crossing the street (Walker et al., 2012). In contrast, pedestrians in a virtual environment who were listening to music or phoning turned out to look more often away from the street environment while waiting to cross the street more often than the undistracted pedestrians (Schwebel et al., 2012). Unfortunately research among pedestrians has not investigated the impact of the use of devices on auditory perception.

It should be noted, however that the studies performed among pedestrians do not always use the same research methods as those among cyclists. Studies into device use among cyclists are observation studies, field experiments or surveys. Besides these methods, research investigating pedestrian behaviour uses virtual environment. The found differences between cyclists and pedestrians can thus (partly) be caused by the various methodology. In general the effects of listening to music and talking on the phone among cyclists are similar to those found among pedestrians suggesting that similar mechanisms may play a role in performance degradation by device use.

Knowledge gaps

Figure 2 shows which relationships (green arrows) and which specific aspects have been researched. As can be seen most research findings concern the relationships between the use of electronic devices and either assessment of traffic situation, cycling performance or self-reported crashes.

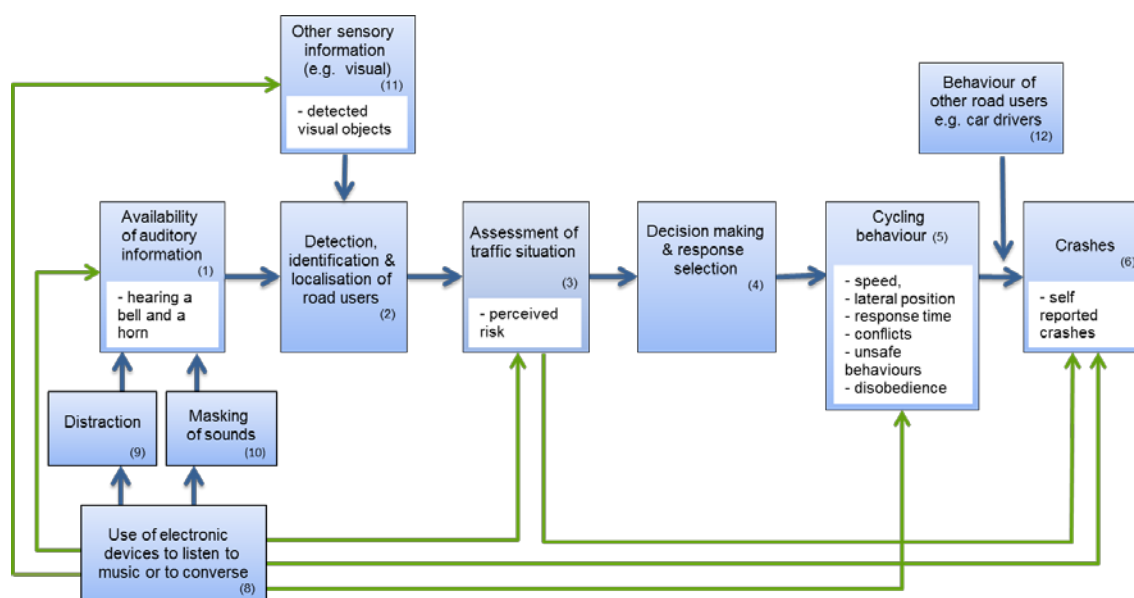


Figure 2 Overview of the relationships (green arrows) examined by the reviewed studies and the specific aspects (in green) they dealt with.

It is difficult to prove that these relationships found in the various studies presented in this paper are (only) due to the limited availability of auditory information. Even if a relation between listening to music or conversing on the phone and the deteriorated performance or (self-reported) crash risk has been found, it cannot be guaranteed that the limited availability of auditory information was the cause of, or even contributed to, the found safety effects. There may be some other aspects related to the use of devices which make it dangerous when used on the road. To start with, some characteristics of cyclists (e.g. those shown at the bottom of Figure 1) who use devices as opposed to those who 'just cycle' can be related to the increased crash risk of the former regardless the limited availability of auditory information. Similarly, the characteristics of traffic environment are likely to influence the impact of the use of devices while cycling. For example, the extent to which cyclists using devices are exposed to hazardous traffic situations is of great importance. If cyclists using devices

cycle more often in complex situations than cyclists not using devices, it is difficult to determine whether the increased crash risk should be ascribed only to the degraded auditory perception resulting from the use of devices or to a combination of both the use of devices and the complex traffic situation. Little is known about the influences of such potentially relevant factors. The already mentioned study of Goldenbeld, Houtenbos & Ehlers (2010) used a statistical correction for influences of a few of these factors, i.e. of the urbanization level, weekly time spent cycling and cycling in demanding traffic situation (such darkness, intersections, heavy traffic). The findings suggest that the use of devices while cycling elevates crash risk independent of these factors. However, as already mentioned, this study concerned self-reported data and generally only (very) light injuries. Objective data including crashes involving fatalities and seriously injured cyclists is missing.

As can be seen in Figure 2, little is known about the impact of the use of devices on auditory perception of traffic sounds. The only research (de Waard, 2011) indicate that the auditory perception is compromised by listening to music and conversing on the phone. The compromised auditory perception is likely to be caused by the limited auditory information reaching the cyclist, either because the cyclist is focussing their attention on the (speech) sounds or because of the masking effects. This means that auditory signals in traffic (such as bell sounds) are likely be missed when cyclists are listening to music or converse on the phone.

As far as the perception of loud sounds is concerned (a horn honking), negative effects of listening to music (but not of conversing on the phone) have been found. In particular response to auditory information was limited when cyclists were listening to music using in-earbuds. Listening to music using one ear bud has been found to hardly impact cycling behaviour and the perception of auditory stimuli. Cyclists listening to music in this way did not miss more auditory stimuli than cyclists not listening to music at all. However, listening to music using one ear bud can influence other aspect of auditory perception, namely the localisation of sounds in space. Sound localisation in the horizontal plane relies mainly on the binaural cues, provided by the presence of two ears. Unless a sound source is located directly in front of or behind the head, sound arrives slightly earlier in time at the ear that is physically closer to the source (e.g. Grothe, Pecka & McAlpine, 2010). This process is distorted when input from only one ear is available. As cyclists are expected to use auditory information not only to determine whether other road users are nearby or approaching but also to determine where the other road users are located in space, listening to music with one earbud may still have negative consequences for cyclist safety.

Because of the limited variation of the sounds used in this study, it is difficult to say to what extent these results apply to other traffic sounds, such as sounds of cars, both conventional and electric. Literature into the detection of cars shows that cars driven in electric mode are more difficult to detect by pedestrians than conventional cars, but only at low speeds and in environments with low ambient noise (e.g. Garay-Vega et al., 2011; JASIC, 2009). However, no research into detection and localisation of (conventional and electric) cars by cyclists in general and by cyclists using electric devices in particular is available. Future studies could focus on this important knowledge gap. Just as research carried out among pedestrians, future studies among cyclists can use various research methods, e.g. laboratory studies using recordings of car sounds or field studies carried out in the real traffic. A laboratory study of Stelling-

Konczak et al. (in prep) focusses first on the ability to localise conventional and electric cars approaching from various directions.

Furthermore, it is also crucial to explore to what extent the use of devices impacts visual detection, i.e. whether relevant visual information is missed. We have seen that the use of devices (conversing on a mobile phone in particular) while cycling can deteriorate peripheral visual detection of stimuli, though the negative effects are not always found. If the use of electronic devices turns out to deteriorate both auditory and visual perception, the possible compensation for the missed auditory information provided by the visual information may not occur. In this case, detection and localisation of other road users will assumingly be affected even to a greater extent.

Finally, no research is available about the perspective of car drivers who encounter a cyclist using electronic devices. Car drivers may, for example, adapt their behaviour to compensate for the possible dangerous behavior of the cyclist, e.g. they may drive more carefully. On the other hand, cyclists who are using devices may annoy car drivers by being distracted and unable to hear approaching cars.

Limitations

As already mentioned, all but one studies presented in this paper were conducted in the Netherlands, raising a question of generalizability of the research finding to other countries. The Netherlands is a country of cyclists, where a bicycling infrastructure is extensive. Practically every Dutch person has a bicycle and uses it regularly. It makes the Dutch setting quite specific. Firstly, Dutch bicyclists may be more experienced and more confident than cyclists in other countries where cycling is less popular. Secondly, the infrastructure may be safer for cyclists in the Netherlands (e.g. due to the presence of separate cycle paths). Finally, Dutch cyclists may be more used to the presence of other 'silent road users' (i.e. other cyclists) and therefore they may rely less on auditory information when detecting and localising other road users. We recommend studying the effects of limited availability of auditory information among cyclists in other countries.

Conclusion

The use of electronic devices turned out to have many negative effects on cyclists. Listening to music and conversing on the phone negatively influences auditory perception, cycling performance and self-reported crash risk. Given the popularity of electronic devices among cyclists and the ambition of many countries to increase the share of electric vehicles, the concerns about limited availability of auditory perception should be taken seriously.

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