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Laboratory results and implications for cycling safety

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Auditory localisation of conventional and electric cars: Laboratory results and implications for cycling safety

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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.

1.1. 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.

1.1.1. 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 alsoWickens' 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., 2011). 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 & Barnecutt, 1996) or a car continuing straight and turning right (e.g. Ashmead et al., 2012; Kim et al., 2012b; Wall Emerson et al., 2011). 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., 2011), 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 Dobreva 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 Mühlenen & 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., 2011). 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. (2011) 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.

1.1.2. 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.

1.2. Methods

1.2.1. 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 HL1 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 1.1*). 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 1.1. Percentage of participants with hearing loss per age.

		Hearing loss
Age group		
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%

1.2.2. 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 1.2.3*) – 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.

1.2.3. 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 1.1* and *3.2*). The participants were seated in a chair at the centre of the circular array of 7 loudspeakers.

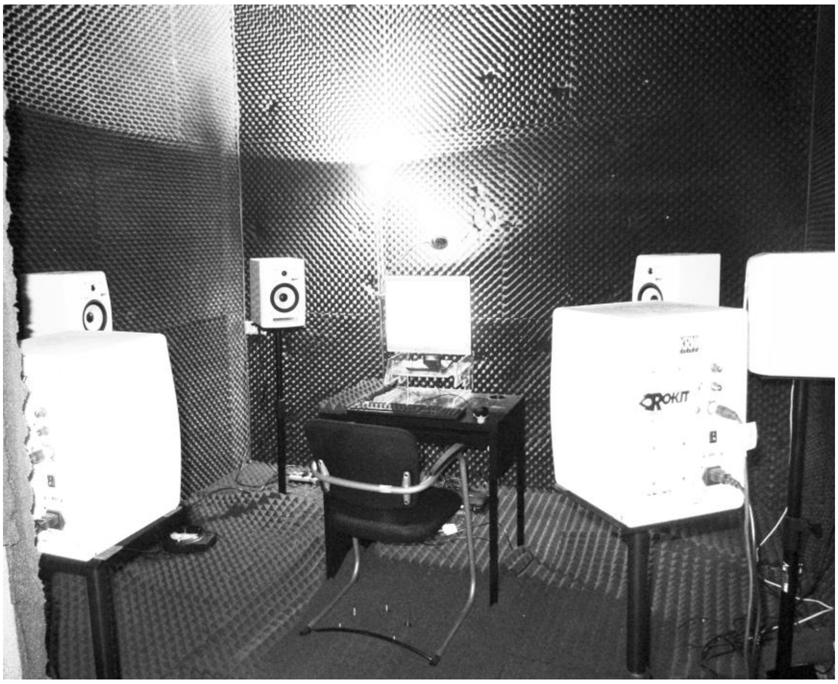

Figure 1.1. Photograph of the lab.

Auditory stimuli were presented in a 2 (car type: conventional versus electric) × 3 (speed: 15, 30 and 50 km/h) × 2 (direction: approaching versus receding) × 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.

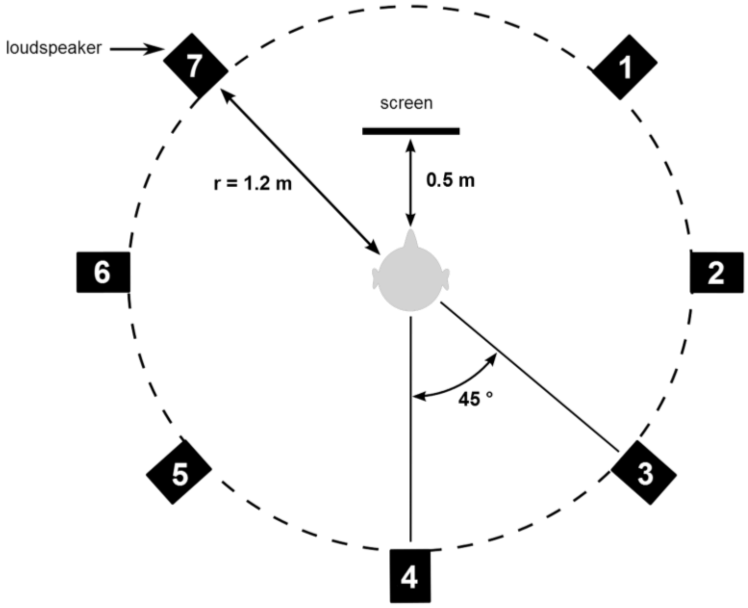

Figure 1.2. Position of the subject and loudspeakers.

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 1.3*). 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.

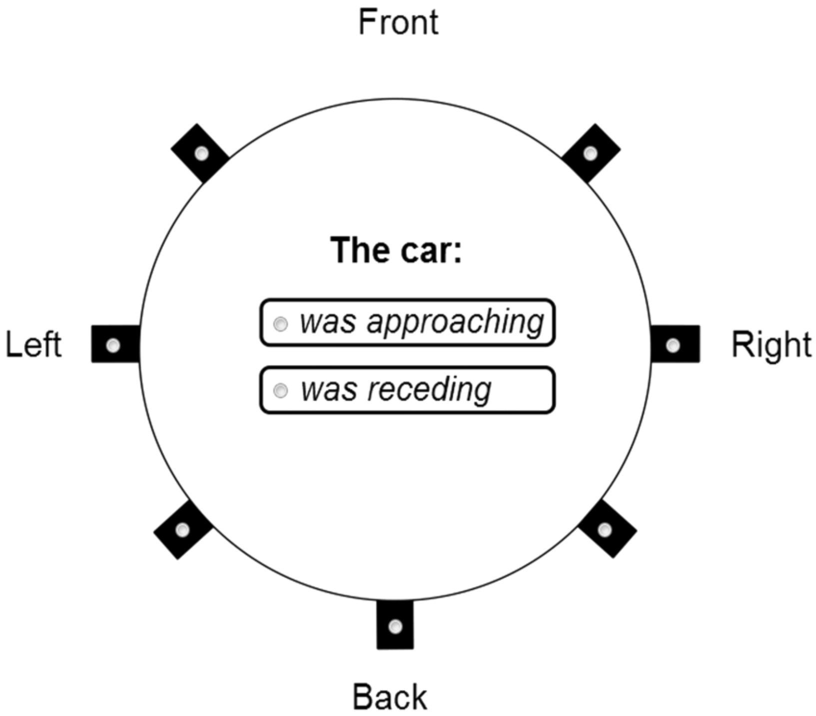

Figure 1.3. Answer options (translated from Dutch) used in the experimental and practice task.

1.2.4. 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 1.2*). 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.

1.2.5. Analysis

All analyses were conducted using the GENLINMIXED 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.

1.3. Results

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

1.3.1. 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 1.3a* and *b*).

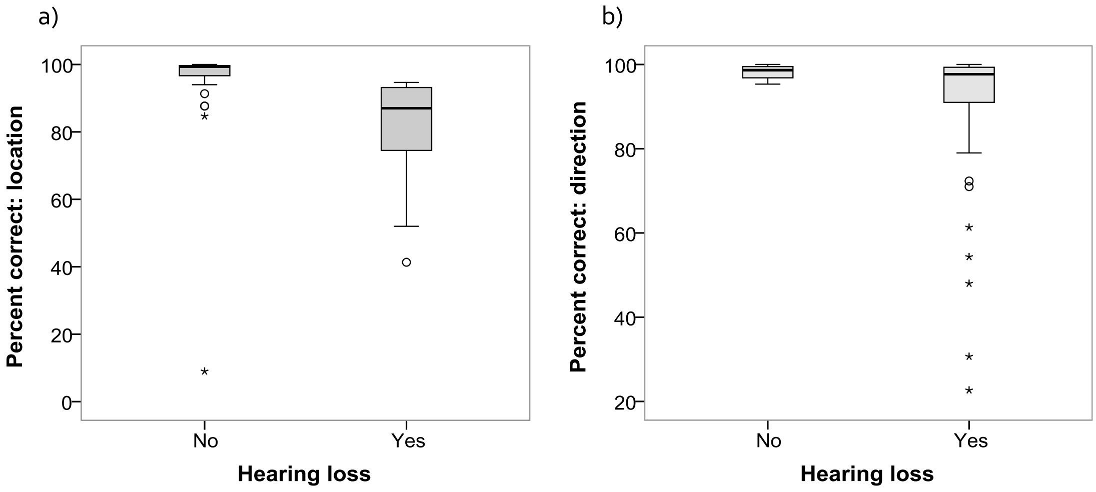

Figure 1.3. Boxplots depicting the spread of the mean percentage of correctly localised cars (pooled for speed, car type, movement direction and ambient sound level): in terms of location decisions (pooled for location) (a) and movement direction (approaching and receding pooled) for participants with 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.

1.3.2. 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 1.4a*). 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 1.4a* 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.

a) b)

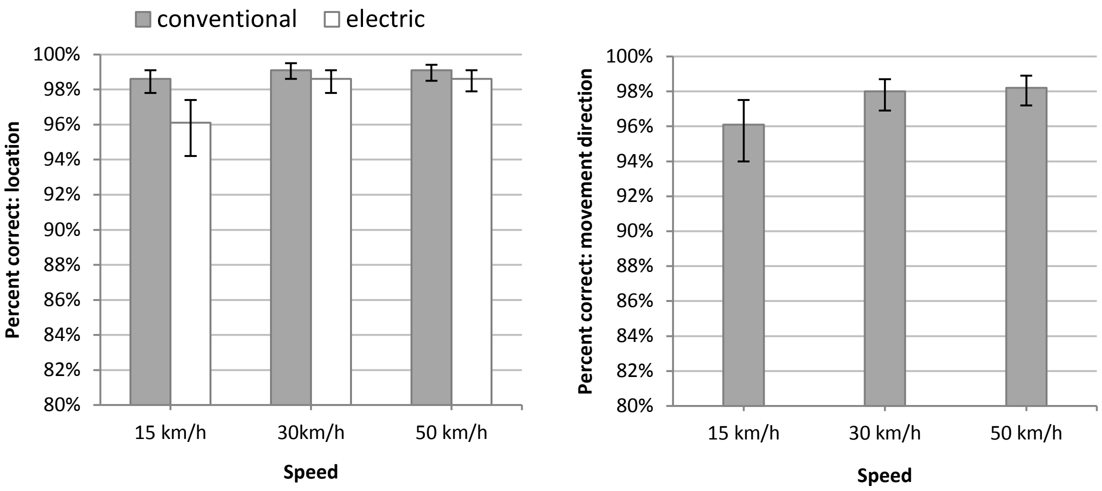

Figure 1.4. Estimated mean location percentages (a) and mean movement direction percentages (b) for car type and age groups. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

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 1.4.b*). No interaction effect between car type and speed was found (inconsistent with hypothesis 1).

1.3.3. 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 1.5a* and *b*).

a)

b)

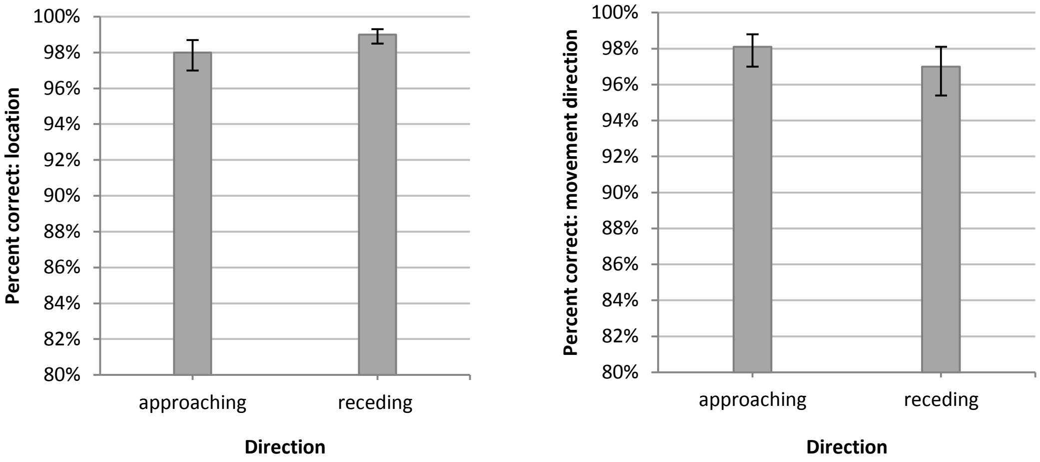

Figure 1.5. Estimated mean location percentages (a) and mean movement direction percentages (b) for approaching and receding cars. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

1.3.4. 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 1.6*) (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).

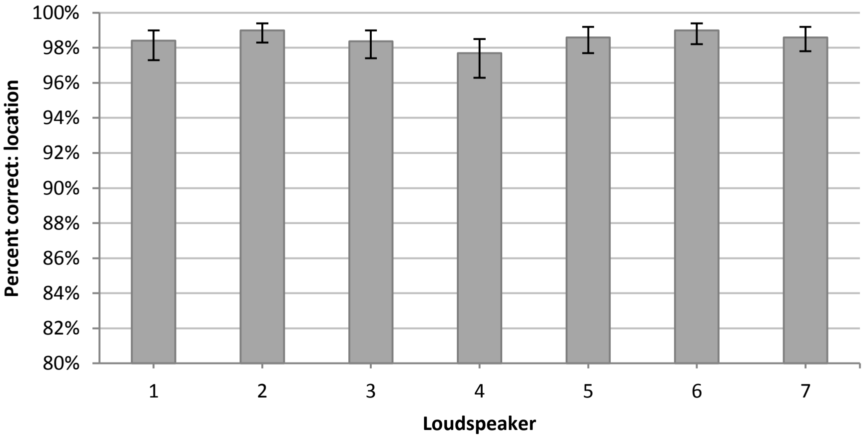

Figure 1.6. Estimated mean location percentages for loudspeaker. The numbers correspond to the position of the loudspeakers shown in *Figure 1.2*. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

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 1.2*).

Table 1.2. Distribution of location scores (in percentages); SP = speaker.

Response								**No response**	**Total**
Sound location	**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

1.3.5. 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 1.7a* and *b*) (consistent with hypothesis 5).

a)

b)

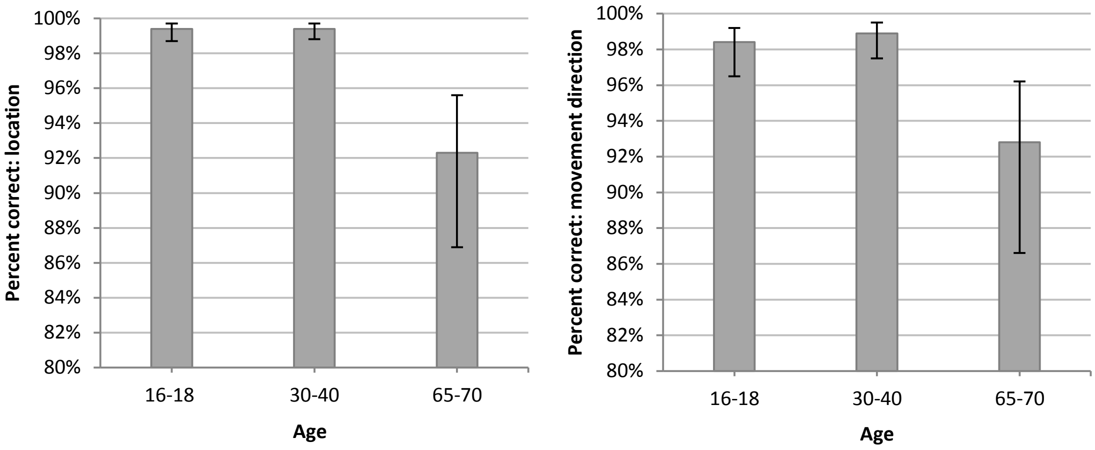

Figure 1.7. Estimated mean location percentages (a) and mean movement direction percentages (b) for age. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

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 1.8a* 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 1.8a*).

Furthermore, a significant interaction effect was also found between direction and age $F(2, 55) = 5.99$, $p = .004$. In *Figure 1.8b* 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.

a) b)

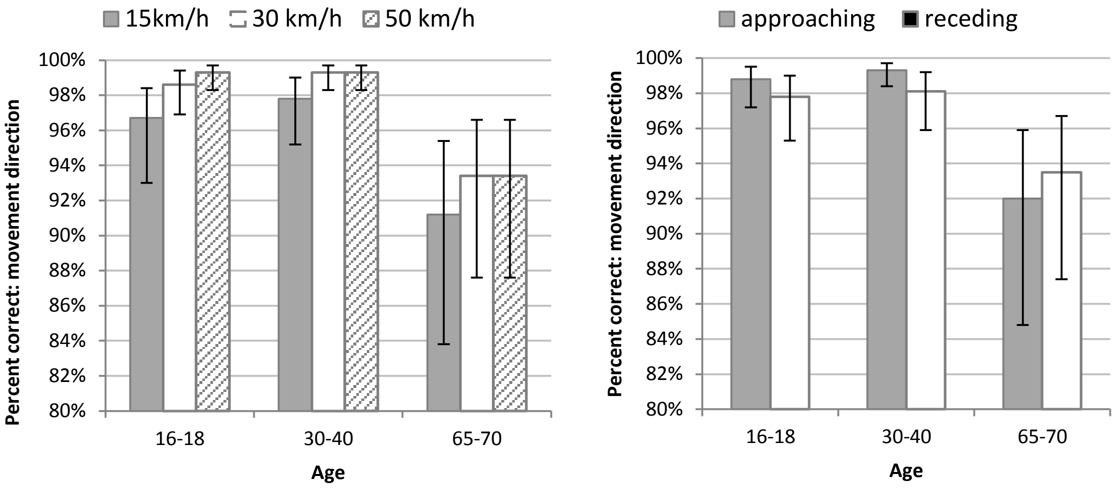

Figure 1.8. Estimated mean movement direction percentages for approaching and receding cars (a) and for speed (b) per age groups. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

1.3.6. Ambient noise

Location decisions were significantly more accurate when the cars were presented in low ambient sound then in moderately noisy ambient sound (consistent with hypothesis 6) *F*(1, 63) = 12.05, *p* = .001 (*Figure 1.9a*).

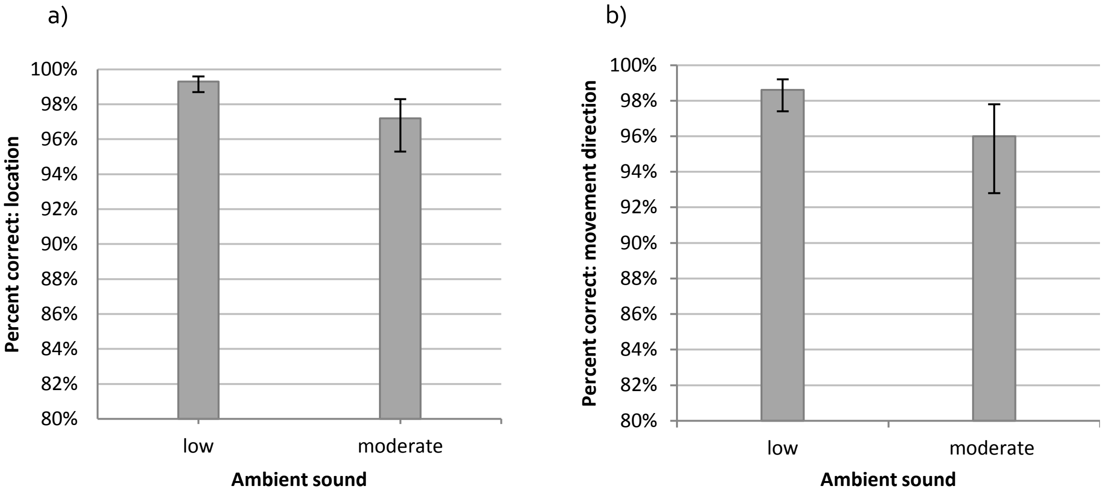

Figure 1.9. Estimated mean location percentages (a) and movement direction (b) for ambient sound level. Error bars reflect 95% confidence intervals. Note: The Y-axis is truncated below 80% to illustrate differences.

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 1.9b*).

1.4. 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.

1.4.1. 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., 2011), 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).

1.4.2. 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.

1.4.3. 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 Mühlenen & 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.

1.4.4. 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; Dobreva, 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.

1.4.5. 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.

1.4.6. 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).

1.4.7. 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.

1.4.8. 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.

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