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Pedestrians' street-crossing decisions compared between conventional and electric vehicles

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ABSTRACT

To safely cross a road before an approaching vehicle, pedestrians need to accurately judge the vehicle's motion. Recent studies from our lab demonstrated that the vehicle sound conveys important information about its motion, particularly in the case of accelerating approaches. Here, we compared street-crossing decisions between conventional (ICEVs) and electric vehicles (EVs) with or without AVAS sounds, presenting both constant-speed and accelerating approaches. To investigate whether the lower sound level of EVs compared to ICEVs contributes to differences in crossing decisions, we additionally presented a condition in which the source levels were matched between vehicle types. All experimental conditions were presented in two modality conditions (auditory-only and audiovisual). The results confirmed that when both auditory and visual information is available, riskier crossing decisions are made for accelerating approaches. This effect of acceleration depended on vehicle type, confirming differences in crossing decisions made in interaction with EVs compared to ICEVs. In the auditory-only condition, there was a massive effect of the vehicle sound level, suggesting that participants heavily relied on sound level when making their crossing decision. Our data thus suggest that reducing vehicle noise levels might imply risks for pedestrians, and that current AVAS designs do notoptimally convey acceleration.

1. INTRODUCTION

The powertrain of electric vehicles (EVs) typically emits lower noise levels than the powertrain of vehicles with internal combustion engine (ICEVs), potentially resulting in lower total vehicle noise levels, at least at lower travel speeds where the tire noise does not dominate. Lower vehicle noise levels are of course highly desirable to reduce the noise pollution near roads. However, from the perspective of traffic safety, particularly for pedestrians and other non-motorized road users, the different acoustic signature of EVs compared to ICEVs creates potential risks. In terms of the importance of auditory information for safe mobility, the auditory detection of vehicles outside the field of view is probably the most important aspect, and current regulations for auditory vehicle alerting systems (AVAS) for electric vehicles were implemented to improve the audibility of quieter EVs at low travel speeds where the road-tire noise is weak [1, 2]. Beyond the aspect of detection, the sound of an approaching vehicle

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provides a rich set of auditory cues to the motion of a vehicle. When crossing a street when a vehicle is approaching, pedestrians need to estimate a) how long it will take for the car to reach their position, and b) judge whether this time is long enough to cross the road safely in front of the vehicle, or whether they should wait until the car has passed them. Thus, pedestrians need to estimate the TTC as accurately as possible to adjust their crossing behavior. When a vehicle approaches a pedestrian, the acoustic intensity of the vehicle sound arriving at the pedestrian increases dynamically, due to the effects of sound spreading (a sound wave propagates away from a source in multiple directions) and -at source-receiver distances above about 100 m - air absorption [3, 4]. In fact, under specific conditions, the rate of change in sound level is inversely proportional to an object's TTC [5-7]. In addition, when an ICEV accelerates while it approaches a pedestrian, the resulting dynamic changes in the powertrain noise provide salient acoustic cues for acceleration, and this acoustic information can be considered particularly important because humans have difficulties in judging acceleration visually [e.g., 8, 9, 10]. To investigate to which extent pedestrians can use auditory information for judging the TTC of approaching vehicles and for making street-crossing decisions, and whether this differs between conventional and electric vehicles, we recently developed a high-fidelity audiovisual simulation system that provides realistic, interactive and physically plausible acoustic simulations of approaching conventional and electric vehicles, combined with interactive visual simulations [11].

Using this system, which we will describe briefly in the Method section below, we found that when only auditory, but not visual information is available, the estimation of the arrival time of vehicles approaching at a constant speed is strongly affected by the intensity of the vehicle sound. When vehicles with identical arrival times were presented, participants estimated louder vehicles to arrive sooner at their position than quieter vehicles [11]. This "intensity-arrival effect" [6, 12] might indicate increased risks posed by quieter vehicles such as electric cars: pedestrians might overestimate the TTC of a quieter EV relative to a louder ICEV with the same actual TTC, which in turn could result in riskier road crossing decisions in interaction with an EV. The effect of vehicle source intensity was still significant but strongly reduced when full visual information about the motion of the vehicle was available [11].

In fact, our previous studies indicate that auditory information becomes much more important for street-crossing scenarios when the approaching vehicles *accelerate positively* (i.e., its travel speed increases continuously). As mentioned, the literature on *visual* TTC estimation consistently shows that humans have difficulty to account for the acceleration of an object [e.g., 8, 9, 10]. Instead, they estimate the TTC of an accelerating object as if it was moving at a constant velocity. For positive acceleration rates, this so-called *first-order TTC estimation* results in an overestimated TTC, because the increase in velocity between the moment of estimation and the arrival of the object is ignored. In [13], we compared TTC estimations for an ICEV approaching at either a constant speed (a = 0) or accelerating during the approach (a = 2 m/s^2) between a visual-only and an audio-visual condition. In the visual-only condition, the TTC estimations showed a clear first-order pattern: with increasing presented TTC, participants increasingly overestimated the TTC, compatible with the literature on visual TTC estimation. However, when the sound of the accelerating ICEV was presented in addition to the visual information, this largely removed the first-order pattern, so that on average the estimated TTC was close to the veridical value. This result was compatible with our expectation that the salient acoustic signature of the ICEV sound during states of acceleration should help pedestrians to factor the acceleration into their TTC estimations. Does this benefit provided by the vehicle sound also apply to electric vehicles? In [14], we obtained TTC estimations for an accelerating ICEV and for an accelerating EV with or without activated AVAS, with acceleration rates between 0.4 and 2.6 m/s^2. At a given simulated TTC at occlusion, the mean estimated TTC increased significantly with the acceleration rate for an EV without AVAS, thus exhibiting a first-order pattern and indicating insufficient consideration of the acceleration. The increase in estimated TTC with the acceleration rate was still significant when the AVAS (compatible with UN ECE R138) was activated on the EV but was somewhat reduced compared to the condition without AVAS. In contrast, for the ICEV, the estimated TTC showed no significant effect of the acceleration rate, indicating that participants were able to use the information about acceleration communicated by the vehicle sound. In [15], we compared pedestrians' street-crossing decisions between an ICEV and an EV with or without activated AVAS, using the same audiovisual simulations as in [14]. We analyzed the probability (denoted by p_{coll}) that a positive crossing decision would have resulted in a collision with the approaching vehicle because the TTC at occlusion was shorter than the time needed to cross the road. For the ICEV, p_{coll} did not increase with the acceleration rate but remained at a relatively low value, similar to the average p_{coll} for constant-speed approaches. In interaction with the EV, however, p_{coll} was on average higher than in interaction with the ICEV and increased significantly with the acceleration rate. With activated AVAS, the mean p_{coll} was slightly lower than without AVAS, but again increased with the acceleration rate. These results indicate that even when full visual information is available, pedestrians' TTC judgments and street-crossing decisions significantly benefit from the information provided by the sound of an accelerating ICEV, but that this benefit is reduced for EVs, even with activated AVAS.

The aim of the present study was to confirm and extend these findings, and to address some methodological limitations of our previous studies. Our simulation system uses a source-based approach, because current simulations of the tire, powertrain and aerodynamic noise do not yet manage to capture all aspects of dynamic driving situations, e.g., the changes that occur with changing speed, acceleration, and engine load. The acoustic source signals are recordings made with microphones attached to the chassis of real vehicles (conventional and electric) while the drivers were trying to maintain a defined constant speed or a defined positive acceleration rate on a test track. Because it is almost impossible to drive with an exact and constant acceleration rate, particularly so for a vehicle with manual transmission, the speed profiles (i.e., the travel speed as a function of time) showed differences between vehicle types, but also between drives intending to represent the same speed profile for the same vehicle type. This variation was particularly pronounced for the ICEV, which had a manual transmission so that gear shifts resulted in a drop of acceleration followed by a short period of increased acceleration. For this reason, the acceleration rates and speeds were not perfectly matched between vehicle types in our previous experiments, which limits the interpretation of the results. To address these methodological shortcomings, for the present experiment we carefully selected time epochs from our vehicle recordings data base where the actually driven speeds and acceleration rates were close to the intended (nominal) values, and therefore also very similar between vehicle types. Also, during acceleration, ICEVs and EVs differ not only in terms of their dynamically changing sound spectrum, but also in terms of the vehicle sound level. To investigate whether the lower sound level of EVs compared to ICEVs contributes to differences in crossing decisions, we additionally presented a condition in which the vehicle sound levels were matched between vehicle types.

2. METHODS

In our simulation system, described in detail in [11, 15], the acoustic simulation was based on recordings of real vehicles driving down a test-track at various velocities and varying levels of acceleration, for an ICEV and an EV. The ICEV was a Kia Rio 1.0 T-GDI 120 (2019, 1.0 l, 88 kW, 3 cylinders) with manual transmission and Continental summer tires (ContiSportContact 5, 205/45 R17). The EV was a Kia e-Niro, 150 kW, 2019, with Michelin summer tires (Primacy 3, 215/55 R17). It was equipped with an AVAS with sound characteristics conform to [1] that could be deactivated. When activated, it emitted sound when the velocity of the car was between 0.5 km/h and 28 km/h. Recordings of the EV were made both with and without activated AVAS. During the drives on the test track, free-field microphones (Roga MI-17) mounted to the chassis of the vehicles recorded the vehicle sound. One of the microphones was positioned centrally on the engine hood, one above the left front tire, one above the right front tire and one above the right rear tire. High-precision GPS tracking was used to measure the position, velocity and acceleration of the car at each timepoint.

In our acoustic simulation, we played back selected time sections of the source signals (i.e., the four microphone signals) via point-sources in the acoustic VR simulation software TASCAR [16]. TASCAR then provides a physically plausible simulation of the dynamic spatial sound field corresponding to the approaching vehicle, including dynamic processing of the geometry of the acoustic scene and acoustic modeling of the sound transmission from the sources to the receiver, providing all relevant monaural and binaural distance and motion cues such as such as dynamic changes in intensity, interaural level difference and interaural time difference, and frequency spectrum. In addition to the simulated vehicle, the acoustic scene also included reflectors (ground surface, house fronts). The simulated scene was rendered by TASCAR on 40 Genelec 8020DPM loudspeakers plus Genelec 7360 APM subwoofer, using a combination of 2D Higher-Order Ambisonics (15th order) [17, 18] for the direct sound (rendered using a subset of the array), and using 3D VBAP [19] for the reflected sound.

The acoustic VR was combined with three-dimensional visual VR. The visual simulations, consisting of a single lane street in a city scene and a red car with a male driver, were presented stereoscopically using a head-mounted display (HTC Vive Pro Eye) with head-tracking. Together, these systems provide an interactive acoustic and visual VR simulation of the recorded drives, where 1) the vehicles can be reproduced at any arbitrary distance from the listener and 2) participants can actively explore the simulated auditory and visual scene with head movements.

The experiment comprised two tasks (measuring TTC estimation and street-crossing decisions). Here, we only present data from the street-crossing task. Participants were presented with an audio(-visual) simulation of a car for 2 s, at which point it was "occluded", i.e., it was no longer audible or visible. The participants' task was to decide whether at the point of occlusion they would cross the road in front of the vehicle ("gap acceptance") or not ("gap rejection") (e.g., [15, 20]). The simulated TTC at occlusion (TTC_{occ}) was varied in an adaptive procedure (see below).

In a within-subjects-design, we presented each of the three vehicles type (ICEV, EV without activated AVAS, EV with activated AVAS) with two velocity profiles. In the simulated accelerating approaches, the acceleration rate was a = 2.37 m/s^2 and the velocity at occlusion was v_{occ} = 28 km/h. In the simulated constant-speed approaches (a = 0), the travel speed was 28 km/h. The experiment contained additional conditions with higher acceleration rates and a higher v_{occ} for some of the vehicle types (shown in italics in Table 1), which will not be discussed here.

From our set of vehicle recordings, we selected 2-s time windows in which the final velocity and the acceleration rate were as close as possible to the combinations of acceleration rate and velocity at occlusion we wanted to present, and where the acceleration during the drive had been as uniform as possible. Two different recordings were selected per vehicle type × a × v_{occ}, to increase the ecological validity. For the constant velocity drives, instead of selecting two recordings, we randomly selected a 2-s section from the available longer recording duration (7 – 20 s) on each trial. The characteristics of the selected recordings are shown in Table 1. The columns "a GPS" and "v_{occ} GPS" illustrate that for all selected recordings, the acceleration rate and final speed were already close to the desired values. When simulating the motion of the vehicle towards the participant in Tascar, we set the acceleration rate to exactly a = 0 or 2.37 m/s^2 and v_{occ} to exactly 28 km/h. Thus, the simulated motion in depth was exactly identical for all three vehicle types.

Table 1: Details of the selected recordings. We show the simulated acceleration (*a Sim*), the mean acceleration in the last 0.5 s during the corresponding vehicle recording on the test track (GPS data; *a* GPS), the simulated velocity at occlusion (v_{occ} *Sim*), v_{occ} during the recording, and the gain that was applied in the level-matched condition.

Vehicle Type	*a* *Sim* (m/s²)	*a* GPS (m/s²)	v_{occ} *Sim* (km/h)	v_{occ} GPS (km/h)	$Gain_{lm}$ (dB)
ICEV	2.37	2.35	28	25.14	4.76
ICEV	2.37	2.33	28	33.41	6.59
EV	2.37	2.34	28	27.37	13.41
EV	2.37	2.53	28	30.10	11.36
EV_{AVAS}	2.37	2.32	28	27.46	12.98
EV_{AVAS}	2.37	2.28	28	27.50	12.71
ICEV	*2.37*	*2.42*	*50*	*49.98*	*0*
ICEV	*2.37*	*2.34*	*50*	*50.61*	***0 (Reference)***
EV	*2.37*	*2.38*	*50*	*49.88*	*5.55*
EV	*2.37*	*2.39*	*50*	*44.99*	*6.79*
EV	*3.30*	*3.26*	*28*	*31.23*	*11.31*
EV	*3.30*	*3.26*	*28*	*30.10*	*11.50*
ICEV	*2.90*	*2.85*	*50*	*50.33*	*-4.54*
ICEV	*2.90*	*2.97*	*50*	*49.61*	*-4.79*
EV	*4.40*	*4.38*	*50*	*44.97*	*5.19*
EV	*4.40*	*4.43*	*50*	*53.82*	*2.92*
EV_{AVAS}	0.00	~0	28	~28	16.39
ICEV	0.00	~0	28	~28	9.52
EV	0.00	~0	28	~28	14.24
ICEV	0.00	*~0*	*50*	*~50*	*1.75*
EV	0.00	*~0*	*50*	*~50*	*6.05*

We presented two level conditions. In the "original" level condition, the vehicle source signals were presented at the sound level recorded on the test track, and thus differed between the ICEV and the EV, and also between the two acceleration rates. In the level-matched condition, the energy-equivalent A-weighted level (L_{Aeq}) in a 0.5 s time window before occlusion was matched between vehicle types for each acceleration rate. We arbitrarily defined one of the ICEV recordings as the reference (see Table 1), and for the other recordings calculated the gain required to equalize the L_{Aeq} in the final 0.5 s. In the level-matched condition, we then applied this gain to the vehicle source signals. The level matching resulted in identical sound levels across conditions when the vehicles were at a distance of 40 m from the listener, but more generally also maintained the sound level differences between conditions within a few dB across a large range of vehicle-listener distances.

Lastly, we varied the modality; the simulated approaching vehicles were presented either only auditorily (A-only) or audiovisually (AV).

For each combination of recording (see Table 1) × modality condition (A-only, AV) × level condition (original, level-matched), we presented two adaptive tracks. A 3-down, 1-up rule [21] tracked the 79.4% point on the psychometric function relating the TTC at occlusion and the probability of accepting the gap (i.e., the TTC_{occ} at which the participant accepted the gap with a probability of 79.4%). A 1-down, 3-up rule tracked the 20.6% "gap acceptance" point on the psychometric function. For the acceleration drives, 15 experimental trials were presented per adaptive track, such that 30 trials were presented per recording within each modality × level-condition combination, resulting in a total of 60 trials per experimental condition (vehicle type × a × v_{occ} × level condition × modality condition). For the constant velocity drives, where only one longer recording was presented from which random 2-s sections were selected, the number of trials per adaptive track was doubled to 30, to also obtain 60 trials per condition. The modality condition was varied between. The adaptive tracks corresponding to the different experimental conditions were presented in a randomly interleaved fashion within blocks.

To analyze the results of the street-crossing task, we fitted a cumulative-normal psychometric function, using a maximum likelihood approach [22], separately for each combination of participant and experimental condition. In the acceleration conditions, trials from the two vehicle recordings were pooled, such that each psychometric function was fitted based on 60 trials. In the constant speed conditions, the psychometric functions were also fitted based on 60 trials.

Before the start of the experiment, we measured the walking speed for each participant, and computed the individual time it would take participants to cross the 3.25-m wide street (t_{cross}). Assuming that the vehicle does not respond to the pedestrian by braking, a collision would result if the participant decides to cross the road (i.e., to accept the gap) even though the TTC_{occ} is shorter than the time required to cross ($TTC_{occ} < t_{cross}$). The probability of such a risky decision (denoted as p_{coll}) can readily be computed from the individual fitted psychometric function and the individual crossing time. The p_{coll} measures how risky a participant's crossing decisions were in a particular condition.

We tested 16 participants. To ensure normal hearing, audiometric thresholds were measured at octave frequencies between 125 and 4 kHz using Békésy audiometry [23]. To ensure (corrected to) normal vision, we assessed the visual acuity using Landolt optotype charts (at a viewing distance of 65 cm to match the effective optical distance in the VR headset) and the stereoscopic visual acuity using a Titmus test [24]. The experiment was conducted in accordance with the principles of the Declaration of Helsinki and ethical approval was obtained from the Ethics Committee of the Institute of Psychology of the Johannes Gutenberg University Mainz (approval number: 2019-JGU-psychEK-S011).

3. RESULTS

Figure 1 shows the mean probability (p_{coll}) of a risky gap acceptance decision that would have resulted in a collision in case the vehicle does not respond to the pedestrian by braking. Two repeated-measures analyses of variance (rmANOVA) on p_{coll} using a univariate approach with Huynh-Feldt correction for the degrees of freedom [25] were conducted, separately for the AV and the A-only condition. The within-subject factors were the acceleration rate (a = 0 or 2.37 m/s^2), vehicle type (ICEV, EV, EV_{AVAS}), and level condition (original, matched). An α-level of .05 was used for all analyses.

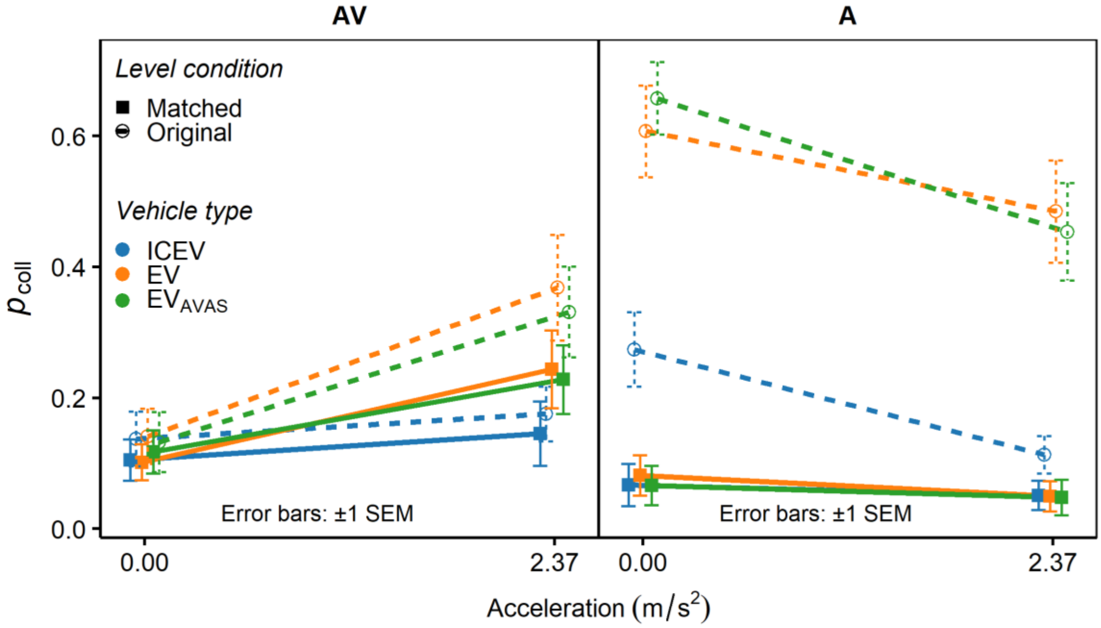

Figure 1: Mean probability of street-crossing decisions that would have resulted in a collision (p_{coll}) as a function of the acceleration rate. Left panel: auditory-visual condition. Right panel: auditory-only condition. Blue symbols: ICEV. Orange symbols: EV without AVAS. Green symbols: EV with AVAS. Dashed lines and open symbols: vehicles presented at the original sound level. Solid lines and filled symbols: vehicles presented at matched levels (see text).

In the AV modality condition (left panel in Figure 1), p_{coll} was significantly higher with a large statistical effect size for accelerating compared to constant-speed approaches of the vehicles, showing that the participants made riskier crossing decisions when the approaching vehicles accelerated, compatible with previous results [15]. Importantly, and again compatible with [15], the increase in p_{coll} in the acceleration conditions relative to the constant-speed condition was larger for the EVs than for the ICEV, confirmed by a significant vehicle type × acceleration rate interaction. This dependence of the increase in p_{coll} when the vehicles accelerated was somewhat larger in the original than in the matched level condition, although the vehicle type × a × level condition interaction was not significant.

In the A-only condition (right panel in Figure 1), p_{coll} showed a massive, significant effect of the level condition with a large effect size, with generally low values of p_{coll} in the level-matched condition but large values of p_{coll} for the EVs in the original level condition. For the ICEV, the collision probabilities in the original level condition were intermediate. The vehicle type × level condition interaction was significant. This pattern is compatible with a strong effect of the vehicle sound level when only auditory, but no visual information is available, as we will discuss below. In the level-matched condition, p_{coll} showed virtually no effect of vehicle type and acceleration rate. In the original level condition, p_{coll} was on average lower for the accelerating than for the constant-speed approaches, showing the opposite pattern as in the AV condition. Additional analyses, which are beyond the scope of this manuscript, indicated that the pattern shown by p_{coll} in the A-only condition can by explained by a level-based decision strategy to a considerable extent.

4. DISCUSSION

In a street-crossing task using high-fidelity acoustic simulations of approaching vehicles, we compared the riskiness of street-crossing decisions between constant-speed and accelerating approaches of the vehicles, and between an ICEV, an EV without AVAS, and an EV with AVAS. The main aim of the experiment was to confirm previous results from our lab concerning these effects [13-15] in an experimental design where the acceleration rates and speeds at occlusion were carefully matched between vehicle types. In addition, we included a condition where the source levels of all vehicles were matched across all presented velocity profiles, to investigate to which extent potential differences between the crossing decisions are driven by differences in vehicle sound level.

When both auditory and visual information was available (AV modality condition), the pattern of results was compatible with our previous findings. On average, participants made riskier crossing decisions in interaction with vehicles that accelerated rather than approached at a constant speed. Importantly, the size of this effect depended on the vehicle type. For the ICEV, p_{coll} hardly increased in the accelerating condition, while for the EV without activated AVAS, the increase was strongest. When the AVAS was activated, this slightly reduced the increase in p_{coll}, but the increase was still stronger than for the ICEV. This pattern matches with our previous results [15]. In the level-matched condition, the difference between vehicle types was somewhat reduced, but the effect was not significant. Thus, it appears that differences in sound level between electric and conventional vehicles play a certain role in pedestrians' better judgments for accelerating ICEVs compared to EVs, but are likely not the most important factor.

In the A-only condition, however, the data did show a massive effect of the vehicle sound level. As indicated by the gains specified in Table 1, the sound levels were generally higher (i.e., positive gains) in the matched compared to the original level condition, for all combinations of vehicle type and velocity profile analyzed here. Compatible with this pattern, low collision probabilities were observed in the matched condition versus high collision probabilities in the original level condition. For the ICEV presented at its original level, which was 5-6 dB higher than for the EVs in the original level condition, p_{coll} was intermediate. These results are compatible with an effect of vehicle sound level on TTC estimation [6, 11, 12], i.e., longer estimated TTCs for quieter vehicles when the actual TTC is identical. The high collision probabilities in the original level condition are compatible with the expectation that participants overestimated the TTCs of the quieter vehicles [11], so that they estimated that at occlusion they had more time available for crossing before the vehicle arrived at their position that was actually the case, resulting in the acceptance of relatively short gaps and a corresponding high collision probability.

For none of the vehicle types and none of the level conditions did the estimated collision probabilities in the A-only condition show riskier crossing decisions when the vehicles accelerated rather than approaching at a constant speed. Instead, in the original level condition, they even showed the opposite pattern as in the AV condition, being lower for accelerated compared to constant-speed approaches. Additional analyses, which are beyond the scope of this manuscript, indicated that this result can at least partially be explained by a sound-level based decision strategy in the A-only condition, i.e., accepting a gap when the sound of the approaching vehicle is still relatively quiet and rejecting the gap when its sound level exceeds a certain critical value In any case, the different patterns observed in the AV condition compared to the A-only condition indicate that participants relied heavily on visual information in the AV condition, with the increase in p_{coll} with acceleration reflecting the well-known failure to fully account for acceleration in the visual modality [9, 13]. To fully confirm this, it would be interesting to compare the results in the AV condition to a condition where only visual information is available. This could show to what extent acoustic information helps participants account for acceleration. Most importantly, the significant interaction between the vehicle type and the acceleration rate in the AV condition shows that acoustic information does help participants account for acceleration, at the very least when the acoustic information is from an ICEV vehicle. For the EVs it is unclear how much benefit, if any, was provided by the acoustic information, as riskier crossing decisions were observed in interaction with accelerating EVs compared to ICEVs.

Taken together, in an experiment with improved methodology, we were able to confirm our previous results that pedestrians can use the vehicle sound to make relatively safe crossing decisions in interaction with accelerating ICEVs, but that the sound emitted by accelerating EVs is apparently less informative, resulting in riskier crossing decisions, even when an AVAS conform with UN ECE R138 is active. In addition, our results clearly confirm that the vehicle sound level is an important factor for pedestrians' crossing decisions, particularly when no visual information is available. Thus, further reducing the sound level emitted by EVs, although certainly desirable from the viewpoint of traffic noise control, implies risks for the safety of pedestrians. Also, it appears that in the design of AVAS systems, there is room for improvement when it comes to conveying information about vehicle acceleration to pedestrians.

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