Multisensory arrival-time estimation of accelerating vehicles: Spectral vehicle sound cues drive the audiovisual benefit

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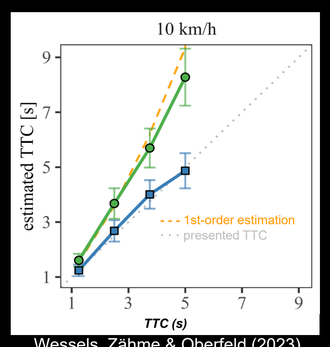
Background: Audiovisual benefit in arrival time estimation for accelerating vehicles

Visual time-to-collision (TTC) estimation: Humans have difficulty factoring in **acceleration**

- Estimates compatible with **1st order estimation;** e.g. Lee *et al.* (1983)

Multisensory benefit in TTC estimation: Estimation error for accelerating vehicles **reduced** when the **sound** of an accelerating vehicle with internal combustion engine 🚗 🔊 is available (e.g., Wessels, Zähme & Oberfeld, 2023)

- But smaller benefit for electric vehicles (e.g., Oberfeld & Huisman, 2024)



Wessels, Zähme & Oberfeld (2023)

This study: Which features of the vehicle sound drive the audiovisual benefit?

Vehicle with combustion engine: **rotational speed** of the engine increases when the driver accelerates (a > 0)

- Change in **frequency spectrum** (frequency of engine orders increases → pitch)
- Increase in **sound power** (powertrain noise ≈ 12 dB per doubling of rotational speed; tire-road noise ≈ 6 dB per doubling of travel speed; Zeller, 2018)

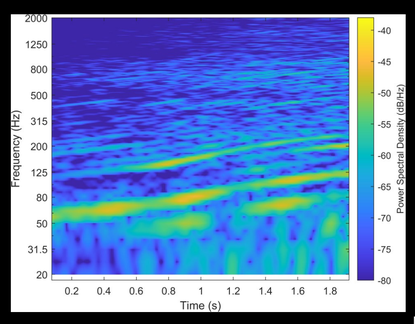
Methods

Research approach

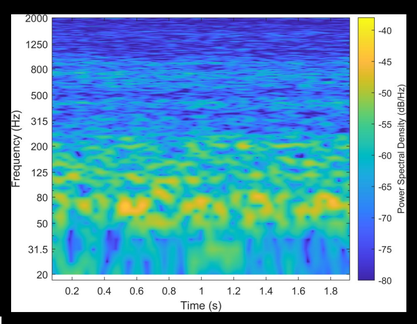
Nullify the acceleration-related change in sound spectrum, sound power, or both

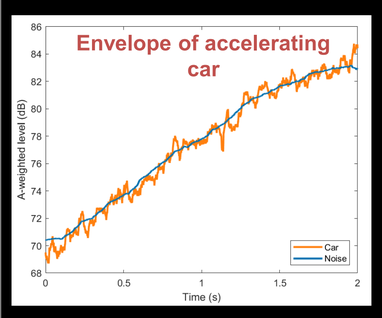
- Source signals: recordings of an accelerating car with internal combustion engine
- Audio signal processing ➔ create 4 combinations of **sound type** and **sound envelope**

Car sound



Noise with same long-term spectrum



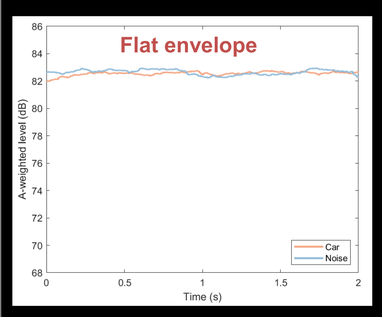


Car sound, *envelope* of accelerating car (original recording)

Acceleration signaled by:
☑ spectrum ☑ envelope

Noise, *envelope* of accelerating car

Acceleration signaled by:
☒ spectrum ☑ envelope



Car sound, *flat envelope*

Acceleration signaled by:
☑ spectrum ☒ envelope

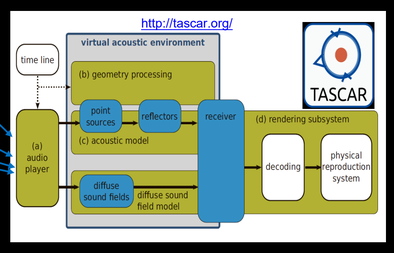
Noise, *flat envelope*

Acceleration signaled by:
☒ spectrum ☒ envelope

Simulation methods and procedure

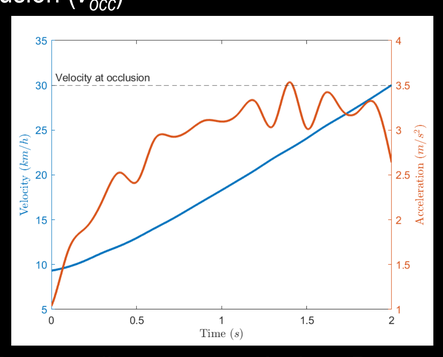
Vehicle recordings | **Acoustic simulation** | **Rendering**

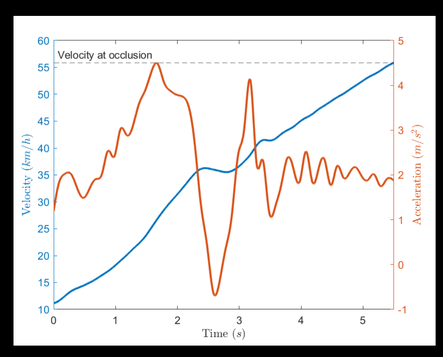
Oberfeld, Wessels & Büttner (2022, *Acc. Anal. Prev.*)



Higher-order Ambisonics

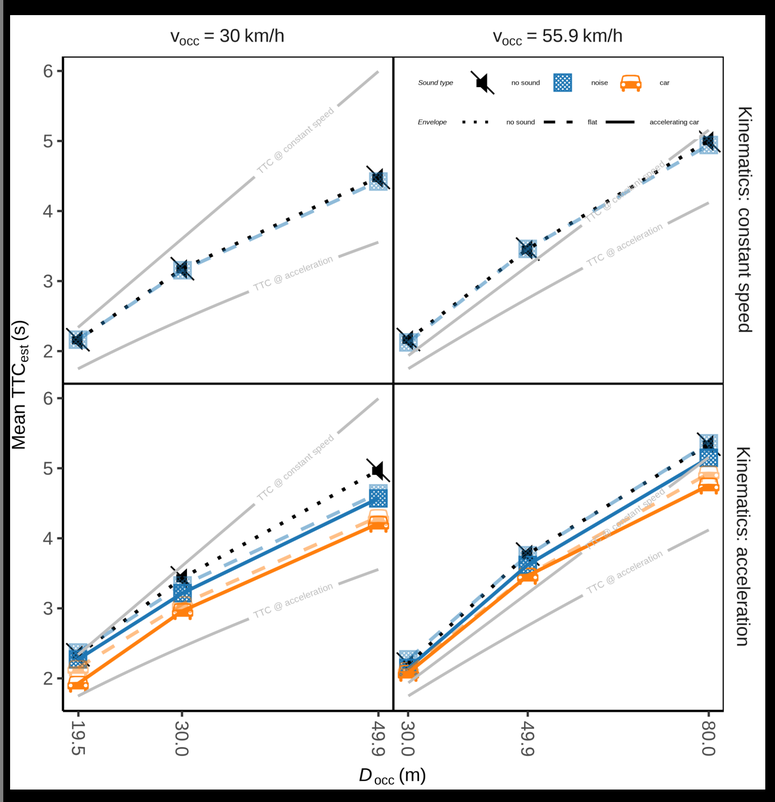
- Pedestrian at the roadside: Simulated vehicle (V-only or AV) approaches for some seconds, then **disappears** ("**occlusion**")
- **Prediction-motion task**: participants (*N* = 25) press response button when they think the vehicle would have arrived at their position
  - **Estimated TTC** = time between occlusion and button press
- **Simulated kinematics**: two *acceleration conditions*, plus *constant speed* with matched velocity at occlusion (v_{occ})





- Per v_{occ}: distance at occlusion (D_{occ}) varied → TTC_{occ} varied between 1.75 s and 6.0 s
- **Task 2**: **magnitude estimation of the acceleration strength** for each vehicle sound (stationary vehicle position; no motion, no visual stimulus)

Results



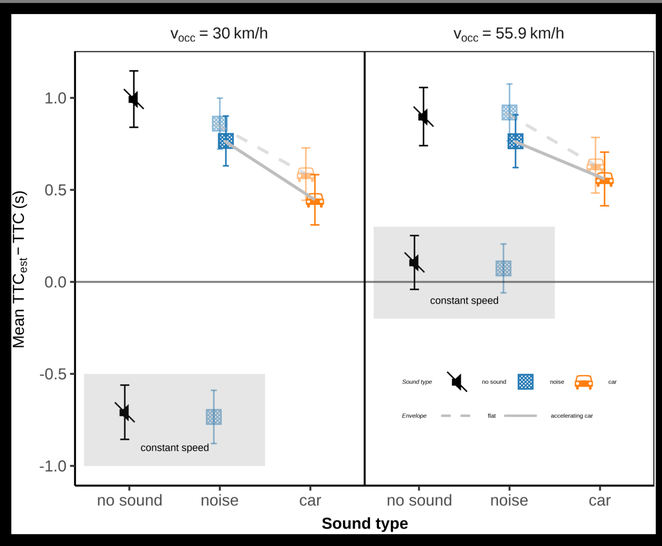
Estimated TTC

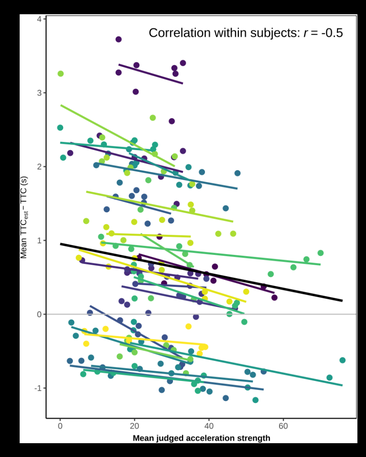
Conditions with *accelerated motion*

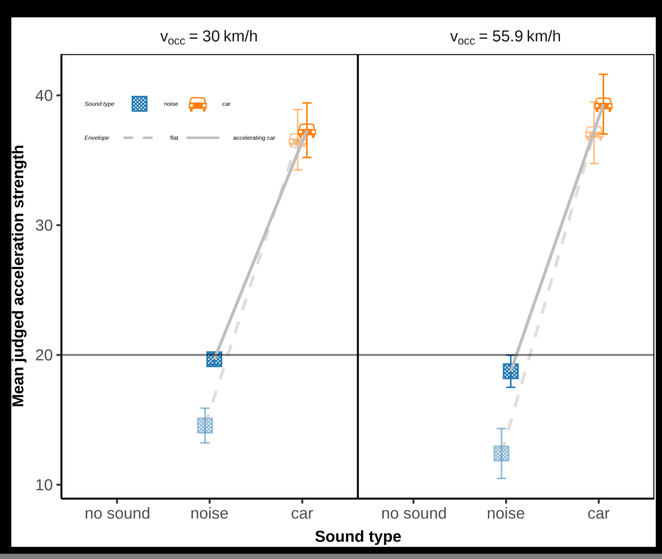
- **Visual-only** 🔇: estimated TTC not shorter than in constant-speed condition at identical v_{occ} and D_{occ} → visual insensitivity to acceleration
- **With sound** (🚗 🚗 ▩): estimated TTC **significantly closer** to the veridical value than in the V-only condition (d_z = 0.5 - 1.7), except when ***both*** the spectral and the envelope cue to acceleration was removed (▩)
- **Within the sound conditions**: effect of the **spectral acceleration cue** (d_z = 2.2, p < .001) stronger than the effect of the **envelope cue** (d_z = 0.97, p < .001)

***Constant-speed* conditions**: no AV benefit

- Compatible with previous data; e.g., DeLucia *et al.* (2025)







Judgments of the acceleration strength

- Large effect of the **spectral cue** (d_z = 2.2, p < .001), weaker effect of the **envelope cue** (d_z = 0.8, p < .001)
- The beneficial effect of the vehicle sound on the estimated TTC **follows** the perceived acceleration strength (sign. within-subjects correlation)

Key findings and perspectives

- **Audiovisual benefit** in arrival-time estimation for accelerating vehicles confirmed
- Acceleration-related **spectral changes** in the vehicle sound shown to be more important than **envelope cues** ➔ implications for the design of AVAS sounds
- **Open question**: What is the mechanism underlying the beneficial effects of the vehicle sound?
  - Second-order estimation when the vehicle sound signals acceleration?
  - Unspecific shortening of the estimated TTC?
  - Higher perceived velocity at occlusion?

References

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