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How does interior car noise alter driver's perception of motion? Multisensory integration in speed perception

S. Denjean[a], V. Roussarie[b], R. Kronland-Martinet[a], S. Ystad[a] and J.-L. Velay[c]

[a]Laboratoire de Mécanique et d'Acoustique, 31, Chemin Joseph Aiguier - 13402 Marseille Cedex 20
[b]PSA Peugeot Citroën, route de Gizy, DRIA/DSTF VV1402, 78943 Velizy Villacoublay Cedex, France
[c]Institut de neurosciences cognitives de la méditerranée, 31 Chemin Joseph Aiguier 13402 Marseille Cedex 20
sebastien.denjean@mpsa.com

Acoustic feedback inside a car is composed of different sources, which give information on the driver's actions and the dynamic state of the car. This acoustic feedback influences the driver's perception of movement in a multisensory integration. The development of electric motorizations brings new balance between noise sources inside the car, due to the loss of engine sound that is present in traditional internal combustion engine cars. To study the influence of this modified noise sources balance on driving, we focused on speed perception. A car simulator was used for this purpose. 24 participants were asked to accelerate up to a given target speed, while the speedometer was hidden. We studied the speed they actually reached with three types of acoustic feedback (engine sound, electric motor sound, no sound), in two visual conditions (night and day). We found that acoustic feedback alters the driver's speed perception.

1 Introduction

Speed management is an important part of driving, as a key factor in road safety. Indeed, speed increases the risk of crash [1] as well as the fatality risk in crash [8]. Drivers have to rely on their speed perception between two glances at the speedometer. Many studies on speed perception have been led in laboratories or in the natural situation (on the road), with different experimental methods. For instance, Evans [3] asked participants in the front passenger seat to estimate the speed on a subjective scale. Milosevic [14] in the same experimental conditions preferred a direct estimation of speed, on an absolute scale (in km/h). Triggs and Berenyi [20] compared passengers' estimation of speed during day and night conditions. Conchillo et al. [2] studied the influence of the traffic on the speed estimation for passengers. Other studies were led in driving simulators, and established relative validity between the car and the driving simulator experiments (for instance [4]). All the studies cited above showed that drivers tend to underestimate speed in both cases, and this tendency is even stronger in a driving simulator.

Speed perception within the context of driving is an everyday example of multisensory integration. Our environment is perceived through a set of perceptual modalities that are combined within the perceptual system. Hence, when perceiving motion, all the sensory cues are combined into global information where each modality can heavily impact each other. A well-known example of multisensory integration involving hearing is the ventriloquist illusion [7] in which the observer mislocates the voice source. We also can cite the McGurk effect [11] where the perceived speech varies with the speaker's lip movements. The effect of auditory cues on visual perception has also been investigated, for instance by Shams, Kamitani and Shimojo [18] who showed that a light spot seems to flash when it is accompanied with multiple auditory beeps. An interesting point is the asymmetrical pattern in cross-modal integration. While visual events strongly affect auditory ones, the opposite effect is weaker. This suggests that vision tends to dominate audition in cross-modal perception. A review of studies related to multisensory contributions to the perception of motion has been given by Soto-Faraco, Kingstone and Spence [19]. This review pointed out that one modality can influence various aspects of perceived motion, such as perception threshold of apparent motion, trajectory or speed.

Automobile noise sources can give information about the vehicle speed. Richard [15] showed that the noise due to aerodynamic and tire-road interaction kept the same spectrum over speeds, but its level was correlated to the vehicle speed. The engine noise is also representative of the engine speed, which variations are highly correlated to the vehicle speed variations between two gear shifts. Many studies have been led on the in-cab perception of engine noise, for instance [16, 17]. For passengers' comfort, modern car design tends to reduce the in-cab noise level without considering the multisensory integration in perceived motion. Moreover, the development of electric motorizations alters the balance of noise sources known from engine cars, due to the loss of engine noise. With quieter motorizations, the engine noise vanishes and the driver only perceives the sound produced by the tire-road interaction and the aerodynamic noises. We cannot predict how these changes will impact the driver's perception of motion. Only a few studies examined the effect of reduced auditory feedback on speed perception. While Evans [3] or Matthews and Cousins [10] reported that drivers tend to underestimate speed to a greater extent when they wear earmuffs, no significant influence from the auditory feedback was found by McLane and Wierwille [12], or by Horswill and McKenna [6]. Nevertheless, these experiments did not mention the degree of attenuation of acoustic feedback. Two studies were conducted on the influence of the acoustic feedback on speed estimation. Horswill and Plooy [5] asked participants to make relative judgments of speed comparing two video based stimuli. The first video used a fixed speed as a reference (60 km/h with the acoustic feedback measured in the car); the second used varying speed (from 48 to 72 km/h) and different sound levels (the level measured in the car and a 5 dB attenuation). Merat and Jamson [13] compared speeds produced by participants in a driving simulator in 3 different conditions: with acoustic feedback and speedometer, with acoustic feedback but no speedometer and without acoustic feedback or speedometer, considering two target speeds: 30 and 70 mph. Both studies showed a significant underestimation of speed with reduced noise level. Merat and Jamson also pointed out difficulties for drivers to maintain a target speed without sound. However, these latter experiments examined the influence of the sound pressure level of the acoustic feedback, but not the nature of this acoustic feedback.

The experiment reported in the present paper aims at studying the influence of changes in the balance between in-cab noise sources due to the development of new motorizations.

2 Method

2.1 Participants

24 volunteers, 22 males and 2 females were recruited for this study. Participants were aged between 18 and 54, (8 between 18 and 24, 8 between 25 and 34, 6 between 35 and 44, and 2 between 45 and 54). They all held a driving license.

2.2 Design

The 'SHERPA' static driving simulator developed by PSA Peugeot Citroën was used for this study. It is composed of the front half of a car placed in front of a semi-circular screen (Figure 1).

Figure 1: Picture of the driving simulator used for the study

To study the influence of changes caused by new motorizations on the driver's perception of motion, we tested three acoustic feedbacks: ENGINE car (noises from engine, wind and tire-road interaction), ELECTRIC car (noises from wind and tire-road interaction), or NO SOUND. In-vehicle sound pressure levels as function of vehicle speed are represented in Figure 2.

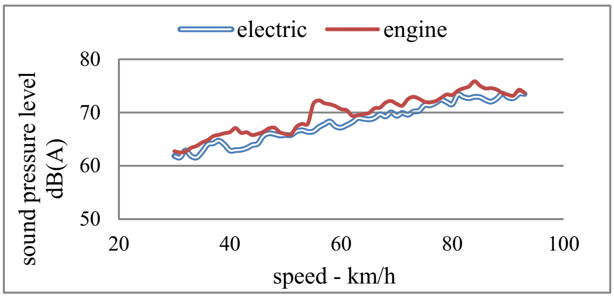

Figure 2: Diagrams of sound pressure levels in relation to vehicle speed

Moreover, as visual information predominates auditory information for speed perception, we wanted to check if the influence of acoustic feedback increased when the quality of the visual conditions decreased. Hence, two visual conditions, DAY and NIGHT, were tested.

Regarding the speed, we studied two target speeds: 70 and 90 km/h, both reached by two different speed gaps, i.e. 20 and 40 km/h (difference between target speed and initial speed). Consequently, four pairs of initial and target speeds were tested (30-70, 50-70, 50-90 and 70-90 km/h)

These experimental variables that were crossed to form a complete experimental design are reported in Table 1.

Table 1: Experimental variables

Acoustic	Visual	Target speed	Speed gap
Engine Electric No sound	Night Day	70 90	20 40

Every stimulus was repeated three times. Consequently, each participant tested 72 stimuli.

2.3 Procedure

The test was divided in two sessions (day and night) of one hour each. In order to reduce learning effects, half of the participants began with the daytime visual condition, while the other half began with the nighttime condition.

The participants were asked to accelerate from initial to target speed, with a hidden speedometer, on a straight two-lane road with trees randomly planted along both sides. No traffic was added to avoid additional disturbance for the driver. Three areas were represented by lines drawn on the road (Figure 3):

- The first area was used to reach the actual test zone. In this area the participant turned on the car, accelerated to reach the initial speed of the acceleration area and switched to the 4th gear. The speedometer was on during this phase.
- As the participant crossed the line and entered the second area, the speedometer was hidden the driver was asked to accelerate to reach the target speed before attaining the next line.
- Finally, in the last area the participant was asked to maintain the target speed reached in the second area.

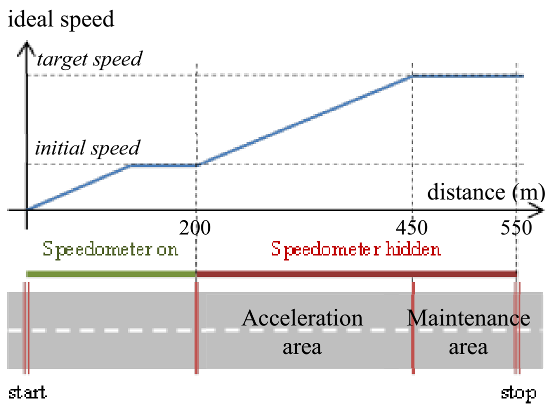

Figure 3: Layout of test areas and ideal speed reached by the participants

At the beginning of each phase, the participants underwent a training period to become familiar with the simulator and calibrate their speed perception.

We chose the ENGINE condition as acoustic feedback for this calibration to create a familiar ambiance in the simulator, since the drivers are used to hearing engine noise when they drive their own cars and therefore might have been surprised by the silence of electric motorization.

For the calibration of direct estimation of speed, participants were asked to accelerate up to the target speed, without speedometer. The experimenter told them which speed they actually had reached, to let them adjust their speed for the next try. After five accurate accelerations (± 5 km/h) for each target speed, the training was over and the test began.

The stimuli were presented to the participants in a random experimental design. The speed actually reached by the participants and their actions (gas pedal depression) were recorded and stored automatically throughout the experiment.

3 Results

We studied the error between the speed actually reached by the participants in the maintenance area and the target speed. We focused on two parameters:

- The mean error of speed along this area, which gives information on the value of the speed perceived by the participants;
- The standard deviation of this error of speed along the maintenance area in order to study the accuracy of the speed maintenance.

Consistency between participants was verified by principal component analysis, while the influence of each experimental variable was verified by an analysis of variance (ANOVA).

3.1 Mean acceleration profiles

Mean acceleration profiles from 50 to 90 km/h in the daytime condition are plotted below (Figure 4).

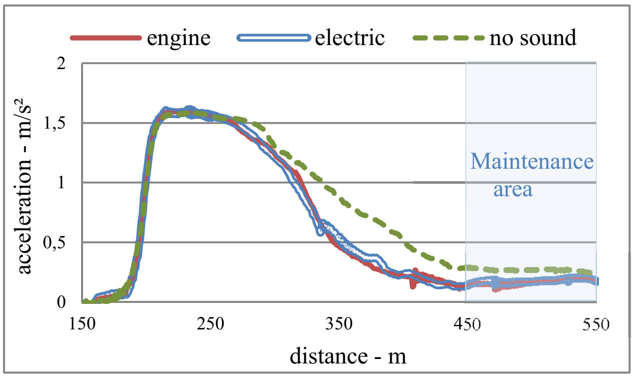

Figure 4: Mean acceleration profiles for the 50 to 90 km/h acceleration in daytime condition

These examples of profiles explain the strategy used by the drivers and reveal that the drivers tried to reach the target speed as quickly as they could, with a mean acceleration of about 1.5 m/s² when they entered the acceleration area, corresponding to an 80% gas pedal depression. Then, they tried to maintain the speed when they believed they had reached the target speed.

We can notice that without acoustic feedback, drivers tended to accelerate for a longer time and accelerated more in the maintenance area. Moreover, in all the acoustic conditions, acceleration was always non-zero and positive in the maintenance area, which means that the drivers kept accelerating although they believed they kept a constant speed.

3.2 Mean speed in the maintenance area

The mean error between the reached speed and the target speed over the maintenance area gives information on the speed perceived by the drivers. We conducted an ANOVA on these errors values to examine the influence of each experimental parameter.

Results of the ANOVA show a significant influence of acoustic feedback on speed perception ($p < 0.001$). This effect is particularly important when no acoustic feedback is presented, in which case the errors are considerably higher than when electric and engine feedbacks are added.

As opposed to the observation we made in a real car, we observe that the underestimation of speed is stronger with engine car feedback, than with electric car feedback. Even if the difference is small, it is significant with a Duncan test.

The ANOVA conducted also points out the influence of the visual condition ($p < 0.001$), with a smaller error in the night condition; and the influence of speed gap ($p < 0.001$) with a smaller error for a 40 km/h acceleration.

The target speed does not have a significant influence ($p = 0.518$).

We also notice the influence of stimuli repetition ($p < 0.001$). The Duncan test conducted on repetition separates the first repetition from the two following, with a smaller error on the first attempt.

Mean error values between experimental and target speeds with respect to acoustic feedback and experimental variables are given below in Table 2.

Table 2: Mean error values (km/h) with respect to acoustic feedback and experimental parameters between speeds actually reached by the participants and target speeds

Acoustic feedback → / Experimental variables		Engine	Electric	No sound
Visual	Day	6.3	5.1	10.9
	night	4.9	4.0	8.6
Target speed	70 km/h	5.7	4.4	9.3
	90 km/h	5.4	4.6	10.1
Speed gap	20 km/h	7.8	7.2	12.0
	40 km/h	3.3	1.9	7.5
Repetition	1	4.6	3.9	8.4
	2	5.8	5.0	11.0
	3	6.2	4.7	9.8

We can notice that drivers underestimated their speed and produced a higher speed than the target speed. All the mean errors are indeed positive. This underestimation is greater without acoustic feedback with errors almost twice as big as in conditions with acoustic feedback.

3.3 Standard deviation of speed in the maintenance area

The way drivers maintain the target speed within the maintenance area was also interesting because it gives a cue about the reliability of speed perception in each condition.

We checked the accuracy of the drivers' maintenance of speed with the standard deviation of the error between the speed that was actually reached and the target speed within the whole maintenance area (blue area in Figure 4).

Results of the ANOVA conducted on the standard deviation of the error on the maintenance area are different from the mean produced speed. We still observe an influence from visual stimuli ($p < 0.011$) with a better accuracy by night, but concerning the speeds, both the speed gap ($p < 0.001$) and the target speed ($p < 0.002$) influence speed perception. At low speeds, drivers more easily maintained a steady speed. This was also the case when the difference between the target speed and the initial speed was small.

The repetition has no longer any influence ($p < 0.607$).

Regarding the acoustic feedback, there is still an influence ($p < 0.001$), but now, the engine car condition gave rise to the best accuracy. Drivers produced a more stable speed with the engine car feedback than with the electric one. The task was most difficult without acoustic feedback. A Duncan test reveals a significant difference between the three acoustic conditions.

Mean standard deviations over the participants are given below, in Table 3.

Table 3: Standard deviation of errors between speeds actually reached and target speed, in relation with acoustic feedback and experimental parameters

Acoustic feedback → / Experimental variables		Engine	Electric	No sound
Visual	Day	0.96	1.07	1.31
	night	0.87	1.01	1.20
Target speed	70 km/h	0.89	0.97	1.18
	90 km/h	0.94	1.11	1.33
Speed gap	20 km/h	0.81	0.99	1.24
	40 km/h	1.02	1.10	1.27
Repetition	1	0.91	1.06	1.20
	2	0.93	1.07	1.28
	3	0.89	1.01	1.28

4 Discussion

4.1 Acoustic feedback

The influence of acoustic feedback is the core of this study. The mute condition shows the importance of in-cab noise in drivers' speed perception. When they drove without sound, participants tended to drive significantly faster.

Even if this is an extreme condition that will never be reached in automotive industry, it reveals that the driving task is strongly affected by the noise perceived inside the car. Surprisingly, we observed that drivers tended to drive faster in the maintenance area for stimuli in which we presented an engine noise feedback, even if the difference with electric feedback stimuli was weak.

On the contrary, we observe that engine noise is helpful when drivers have to accurately maintain the speed. Engine noise gives information to the driver about the engine speed, which is correlated to the vehicle speed. This information is easily treated by the driver. A change in engine noise pitch means that the engine speed, and thus the vehicle speed, varies. Consequently, engine noise gives precious information for speed maintenance. Once more, in extreme conditions with no acoustic feedback, the task was much harder and participants had many difficulties in maintaining a steady speed. This difficulty increased as the mean speed values increased.

4.2 Speeds

Concerning the target speed, we did not observe significant differences, but the target speeds were very close (only 20 km/h difference); a speed effect might appear with a greater difference in the target speeds.

On the contrary, the speed gaps seemed to influence speed perception. We observed that the deviation between the speed that was actually reached and the target speed was higher for a 20 than for a 40 km/h acceleration. On the first hand, this result might be due to a protocol bias caused by the fact that the acceleration areas have the same length for both speed gaps. As seen in Figure 4, the participants kept accelerating when they believed they were maintaining their speed. Moreover, as drivers tried to reach the target speed as quickly as possible, they had a longer distance to travel before they reached the maintenance area for a 20 km/h acceleration than for a 40 km/h acceleration. Consequently, when they reached the maintenance area, their speed derived to a greater extent towards higher speeds with a lower speed gap. However, even if there might have been an experimental bias due to the length of the acceleration area, this does not infer with the conclusions of the study because the relative influence of acoustic feedback is robust to initial and target speeds. On the other hand, we observed that the mean acceleration produced by all the drivers was higher at the moment they reached the target speed for a 20 km/h acceleration than for a 40 km/h acceleration.

The results are different for the maintenance accuracy: the lower the target speed and the speed gap, the more accurately the drivers maintained their speed. Participants more accurately maintained a low speed and even more with a low speed variation, a result consistent with that of Merat and Jamson [13].

4.3 Visual

The ANOVA conducted showed that the mean error between actual and target speeds was lower by night. By night, drivers tended to drive slower than by day because they had less visual marks and less easily anticipated their trajectory. Consequently, drivers who underestimated their speed more closely approached the target speed by night since their speed was reduced due to the degraded visual condition.

However, in a driving simulator, participants do not feel the same risky situation as in a real car. Hence, we would think that they would reduce their speed to a lesser extent due to the fact that they do not see a long distance ahead and focus their perception on the lateral stream, which gives a better estimation of speed perception, particularly in low light conditions. Lower speed by night is consistent with previous studies [9].

5 Conclusion

In agreement with previous studies on speed perception, we observe that drivers tended to underestimate their speed while they were driving. Moreover, this underestimation was greater in daytime than in nighttime conditions. In this study, we focused on the acoustic feedback perceived by the driver inside the car. We did not study the influence of sound pressure level, but the nature of the noise per se. More precisely, we pointed out the influence of the engine noise. We can see that acoustic feedback seems to be very important in the steady speed maintenance task. Drivers underestimated their speed to a greater extent when no acoustic feedback was present and tended to drive faster than in conditions in which acoustic feedback was present. The engine speed information given by engine noise was helpful when the driver had to accurately keep a steady speed. These results were robust to the target speed we asked the subjects to reach and the acceleration they had to produce.

Non-accurate absolute estimation of speed by drivers does not really matter in natural driving tasks, since they can use their speedometer to check their speed. Nevertheless, it could be more problematic between two glances at the speedometer. Consequently, relative estimation of speed is necessary for drivers. They should be able to keep a constant speed while focusing on the road. As revealed by the present study, engine noise is a useful source of information to stabilize speed. We can therefore infer that the lack of motor noise in electric motorizations can make it difficult for the driver to respect speed limitations, which might increase risks on the road.

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References

[1] L. Aarts, I. van Schagen, "Driving speed and the risk of road crashes: A review", *Accident Analysis and Prevention* 38, 215-224 (2006)

[2] A. Conchillo, M.A. Recarte, L.M. Nunes, T. Ruiz, "Comparing speed estimations from a moving vehicle in different traffic scenarios: Absence versus presence of traffic flow", *The Spanish Journal of Psychology* 9(1), 32-37 (2006)

[3] L. Evans, "Speed estimation from a moving automobile", *Ergonomics* 13, 219-230 (1970)

[4] S.T. Godley, T.J. Triggs, B.N. Fildes, "Driving simulator validation for speed research", *Accident Analysis and Prevention* 34, 589-600 (2002)

[5] M.S. Horswill, A.M. Plooy, "Auditory feedback influences perceived driving speeds", *Perception* 37, 1037-1043 (2008)

[6] M.S. Horswill, F.P. McKenna, "The development, validation, and application of a video-based technique for measuring an everyday risk-taking behaviour: Drivers' speed choice", *Journal of Applied Psychology* 84, 977-985 (1999)

[7] I.P. Howard, W.B. Templeton, *Human spatial orientation,* Wiley*,* New York (1966)

[8] H.C. Joksch, "Velocity change and fatality risk in a crash - A rule of thumb", *Accident Analysis and Prevention* 25(1), 103-104 (1993)

[9] A. Kemeny, F. Panerai, "Evaluating perception in driving simulation experiments", *Trends in Cognitive Sciences* 7(1), 31-37 (2003)

[10] M.L. Matthews, L.R. Cousins, "The influence of vehicle type on the estimation of velocity while driving", *Ergonomics* 23, 1151-1160 (1980)

[11] H. McGurk, J. MacDonald, "Hearing lips and seeing voices", *Nature* 264(5588), 746-748 (1976)

[12] R.C. McLane, W.W. Wierwille, "The influence of motion and audio cues on driver performance in an automobile simulator", *Human Factors* 17, 488-501 (1975)

[13] N. Merat, H. Jamson, "A driving simulator study to examine the role of vehicle acoustics on drivers' speed perception", *Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design,* 226-232 (2011)

[14] S. Milosevic, "Perception of vehicle speed", *Revija za psihologiju* 16, 11-19 (1986)

[15] F. Richard, F. Costes, J.-F. Sciabica,, V. Roussarie, "Vehicle Acoustic specifications using masking models", *Proceedings of the Internoise*, Istanbul (2007)

[16] J.-F. Sciabica, M.-C. Bezat, V. Roussarie, R. Kronland-Martinet, S. Ystad, "Caractérisation des variations de timbre du bruit moteur dans l'habitacle automobile par application d'un modèle auditif" *10ème Congrès Français d'Acoustique*, Lyon (2010)

[17] J.-F. Sciabica, M.-C. Bezat, V. Roussarie, R. Kronland-Martinet, S. Ystad, "Towards the timbre modeling of interior car sound", *Proceedings of the 15th International Conference on Auditory Display*, Copenhagen (2009)

[18] L. Shams, Y. Kamitani, S. Shimojo, "Visual illusion induced by sound", *Cognitive Brain Research* 14, 147-152 (2002)

[19] S. Soto-Faraco, C. Spence, A. Kingstone, "Cross-modal dynamic capture: Congruency effects in the perception of motion across sensory modalities", *Journal of Experimental Psychology* 30(2), 330-345 (2004)

[20] T. Triggs, and J. S. Berenyi, "Estimation of automobile speed under day and night conditions", *Human Factors* 24, 111-114 (1982)