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COMPARISON OF ACCOMMODATION SPEED AND READING ACCURACY FOR CONVENTIONAL AND DIGITAL REAR-VIEW MIRRORS WITH EMPHASIS ON OVERALL TRAFFIC SAFETY

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The topic of this article is a comparison of the speed of accommodation and the reading accuracy of conventional and digital rear-view mirrors. The data for the research described in this article was obtained through laboratory measurements using precise measuring techniques on a medium-sized, relatively heterogeneous group of users, consisting mainly of university students and employees. In the experiment, all research participants performed a series of test tasks on two identical passenger vehicles, where one was equipped with conventional side mirrors, while the other had digital side mirrors installed. The main reason for carrying out this study is to try to imitate a common situation where the driver is forced to drive a car with these modern technologies in normal traffic and to understand the specific issues associated with the use of this technology. The speed of accommodation and reading accuracy is a very important parameter in this regard, which is also important for maximizing road traffic safety. The data obtained from this research was subsequently subjected to selected statistical analysis. Results confirmed statistically significant differences in the speed of accommodation when reading data from conventional and digital mirrors. It has been shown that the use of digital mirror technology can have a direct negative effect on road safety, especially in combination with other negative effects given by the technical nature of the technology under investigation, such as image latency in digital displays.

Keywords: digital mirrors; ergonomics; automotive; rear view; eyes; ophthalmology

Driving a vehicle is a challenging task, despite all the improvements and assistants available to the driver today. Since 1886, when Karel Benz introduced the first car, the automotive industry has undergone significant changes in both exterior and interior areas (Dowlen, 2013). Engines have become more efficient and reliable, cockpit structures are more stable, and other elements have been added to the vehicle to ensure the comfort and safety of the driver. At the same time, however, the speed of vehicles and the density of traffic have increased significantly, and thus the demands on driver´s skills have also increased (Regan and Horberry, 2014). Person´s limits are very variable; it is necessary to generally respect them so that the driver is not pushed to reach their limits. A particular task can only be performed if individual human capacity exceeds the demands of the task (Kroemer and Grandjean, 1997). Audiovisual technologies, newly used in vehicles, provide the driver with a wide range of information, but also, on the other hand, represent an ever-increasing information load to which the driver is exposed (Häne et al., 2017; Hruška and Jindra, 2016).

Along with increasing psychological demands on the driver, the influence of the human factor on accidents caused by inability to control the car, the misinterpretation of the provided information, or overloading of driver´s cognitive functions is becoming more frequent (Edwards et al., 2011). Today, these situations increasingly lead to considerations of replacing the human factor with fully autonomous vehicle control. However, this technology still has a long way to go and therefore it is necessary to choose other solutions (Huhtamo, 2020). Today, car manufacturers are increasingly going the route of the maximum digitization of all information interfaces. This also applies to rear-view mirrors.

Human senses are evolutionarily adapted to survival in nature, and for human survival in modern society, they often reach their limits, which are not always and completely understood. Vision is of course the most important sense in this context, and one of its basic parameters is the ability to accommodate, i.e., refocusing from distance to near and back (Logan et al., 2021; Benjamin, 2006). This

ability is key in the process of driving a motor vehicle, and the speed of accommodation directly affects road safety. Repeated and prolonged forced visual accommodation can lead to a deterioration of accommodative amplitude (Sullivan, 2008). The need to use visual accommodation is one of the essential differences between conventional rear-view mirrors and digital rear-view mirrors (Babu et al., 2022). Due to the physical nature of the optical system, it is not necessary to use visual accommodation with conventional rear-view mirrors, and the driver basically always focuses on the same distance (practically to infinity). The eye is thus in a relaxed state and is not strained. In the case of digital size mirrors, it is necessary to refocus repeatedly due to the use of digital displays instead of regular mirrors. The eye must therefore necessarily increase the optical power of the optical system of the eye by accommodation, i.e., by changing the radius and position of the lens, using the zonular fibres of the ciliary muscle. Focusing on close range thus represents a straining process for the eye, while it is true that the closer the eye must focus, the greater the accommodation effort must be expended (Glasser and Campbell, 1999).

The aim of this work is to find out whether and how the reaction time is needed to read the selected text changes, with conventional vs digital rear-view mirrors. The research hypothesis is that the reaction time needed to read the selected text will be longer with digital rear-view mirrors when compared to conventional mirrors, mainly due to the necessary visual accommodation of the driver.

The main contribution of this work lies in the assessment of the difference between the technologies of conventional and digital mirrors from the point of view of ophthalmology as well as ergonomics. The main parameter for assessing both technologies is, in the case of this work, accommodation, which is an important physiological process of the eye. This process has a direct impact both on the health of the driver and in an immediate action on traffic safety. Although the described results are not favourable for the newer technology and the contribution of the work cannot be seen as a specific positive innovation, the authors believe that even revealing the negative aspects of emerging and newly used technologies, from the point of view of their impact on human health, is a positive and beneficial process.

Material and methods

Sample size and group description

A relatively heterogeneous group of 54 volunteers were selected to participate in this research, from whom basic sociodemographic data were collected. Specifically, it was about age, gender, and whether they had previous experience with digital mirrors. The age of the participants ranged from 20 to 59 years (Fig. 1). The only condition for participation in the research was that the respondent did not actually wear glasses while driving. This condition arose due to the measurement technique used – special glasses for tracking the movements of the human eye. All respondents also underwent an initial ophthalmological examination to diagnose any visual defect. Respondents who were diagnosed with a visual defect were processed in a separate file, which is not part of this work.

Location

The research took place in a closed building with consistent lighting conditions. The location for measurement was chosen due to sufficient free space for measurement and to ensure constant conditions during all measurement sequences. The research was therefore not influenced by weather or daytime.

Equipment description

Special recording glasses "Tobii Pro Glasses 2" was used as an essential tool to collect (record) the visual and audio track during the measurement. The software Tobii Pro Glasses Analyzer and "Shotcut" (an open source, cross-platform video editor) was used for subsequent analysis of the data obtained. Two mass-produced Škoda Superb III station wagon cars were used for testing. One of the vehicles was modified, while both side mirrors were removed and replaced with digital side mirrors. A Sony CyberShot Camera DSC-RX0 Mark II was used to capture the image and display the image on the FeelWorld FW570 monitor.

The parameters of all devices are described in detail in Table 1. The connection of the sensing and display device was ensured by a cable. The location of the displays was chosen to correspond to the conventional view axes of rear-view mirrors, i.e., from the inside on the front side windows (Beck et al., 2021). The camera was set to such a zoom that the case on the screen corresponds to the size on the reflective surface of a conventional mirror. The image on the screen had to be mirrored so that the resulting image corresponded to reality, or the image provided by a conventional mirror. The distance to the right display was 1,090 mm, and the distance to the left display was 550 mm from the centre position of the head of the 50-percentile adult

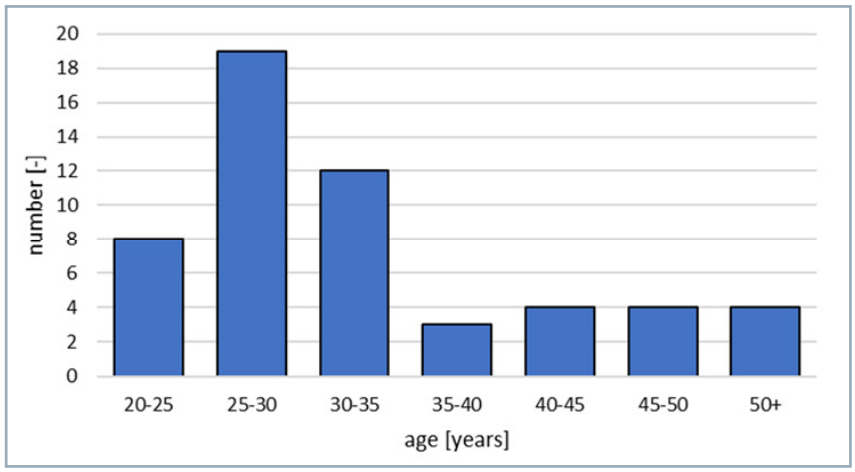


Fig. 1 Age distribution of participants

Table 1 Equipment description and specifications

Equipment	Description	Specification
Display	screen size	5.7″/14.5 cm
FeelWorld F570	resolution	1,920 × 1,080 pixels (16 : 9)
	brightness	460 cd·m^{-2} (LED)
	dimension	(5.8 × 3.2 × 0.7)″/(14.8 × 8.2 × 1.9) cm
Camera	resolution	4,800 × 3,200 pixels (3 : 2)
Sony DSC-RX0 II	sensor type	BSI – CMOS
	processor	BIONZ X
	focal length (equiv.)	24 mm
	max. aperture	F4
	normal focus range	7.87″/20 cm

male mannequin, which is considered to be the optimal seating position in a car. The positions and angles of the digital displays were fixed in the vehicle and could not be changed by the participants. Display surfaces were positioned at right angles to the view axis controller to the centre of the display surface (Fig. 2).

In order to ensure a uniform point, which was used to start the measurement, a conventional traffic light was chosen. Each participant had to focus on the red traffic light at the beginning of measurement. This traffic light was mounted on a stand at a height of 1.3 m. Its control was handled by a switch, which was placed so that its operator could not be seen.

A double-sided rotating magnetic board (flipchart) with dimensions of a usable area of 100 × 80 cm was placed in the space behind the car (Fig. 3). The magnetic plate was rotatable so that a word could be formed from individual letters without being seen from the driver´s point of view. The participant watched the traffic light intently, and the board was only turned after the signal. Then, the participant read the prepared word. The letters were printed on A4 paper. Size, font, and the number of letters were chosen according to ISO 8596: 2018 – Sloan font, size 625 pt. Letters were mirrored and placed from the right to the left so that it is normally legible when viewed in a mirror, i.e., from the left to the right (Fig. 3). A list of approximately 500 commonly used Czech words was chosen, from which one was always randomly selected for the given test. A list of about 400 commonly used English words was also selected for English-speaking participants. These were always five-letter words that are well known and commonly used. The testing scheme can be seen in Fig. 4. The traffic light was located 6 m from the rear side cover mirrors so that it lies in the axis of the car and the driver can see it clearly. The flipchart was behind the car at a distance of 6 m from the reflective surface of the side mirror, or from the camera lens of the digital side mirror. Spotlights were lit on the board from the space just behind the car.

Two VECT reflectors were used to maintain the same illumination of letters on the board DSR-4x55WT (Fig. 3), which are tubular studio lights made of pure aluminium.

Methodology and data collection

Each participant filled out an entry questionnaire in which they entered their basic data. The participants then underwent an ophthalmological examination, where experts measured their vision and eventually diagnosed if the participant had any visual defects. The participants

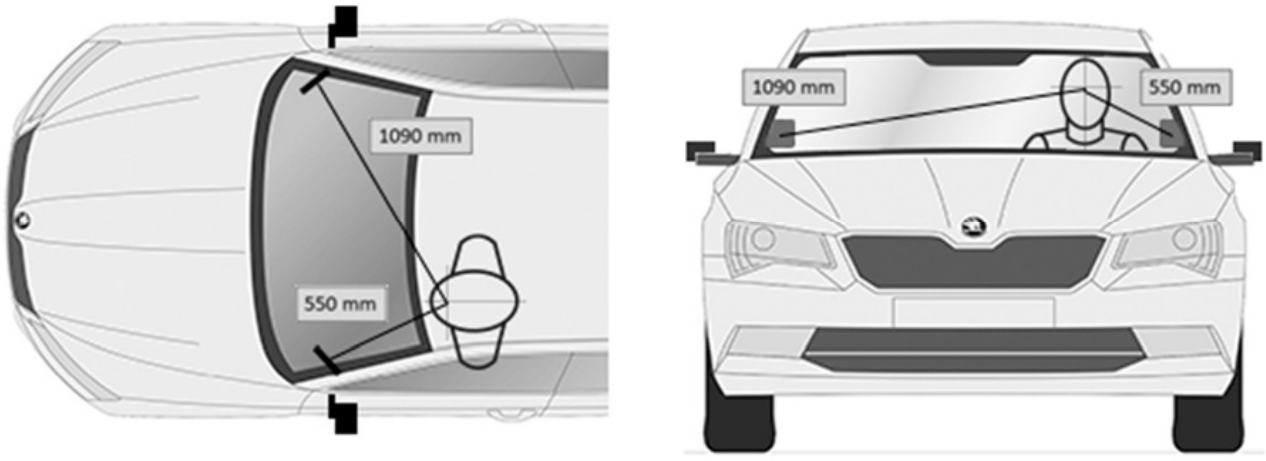


Fig. 2 Dimension to side mirrors from the centre of the head of 50-percentile human head
top view – left; front view – right



Fig. 3 Traffic light (on the left side), whiteboard with a compound word (on the right side)

were then asked to wear the Tobi Pro Glasses 2, which were calibrated and then placed in one of the cars (Fig. 4). In order not to affect the results, the first car was changed, i.e., if the first participant started the test in a car with conventional mirrors, the second participant started his test in a car with digital mirrors. After sitting down, each participant adjusted their seat and the position of the mirrors so that they had a good view of the flipchart with the text. Once the participant was ready, a red light came on at the traffic light for the participant to focus on. The light had to be turned on for at least 4 seconds to allow the eye to adjust to the distance of the traffic light (simulating the visual accommodation to infinity) (Lockhart and Shi, 2010). During this interval, the flipchart was rotated, where a specific selected word was prepared. After concentrating on the red traffic light at a distant point, the traffic light would change from red to green when the participants had to look into the display located at a distance of 550 mm or 1,090 mm from the eye. As soon as the lights changed to green, the participant first looked in the left mirror and read the word aloud as quickly as possible. The same process was repeated with the right rear-view mirror. A new word was selected after each trial. The test was repeated twice for each side mirror.

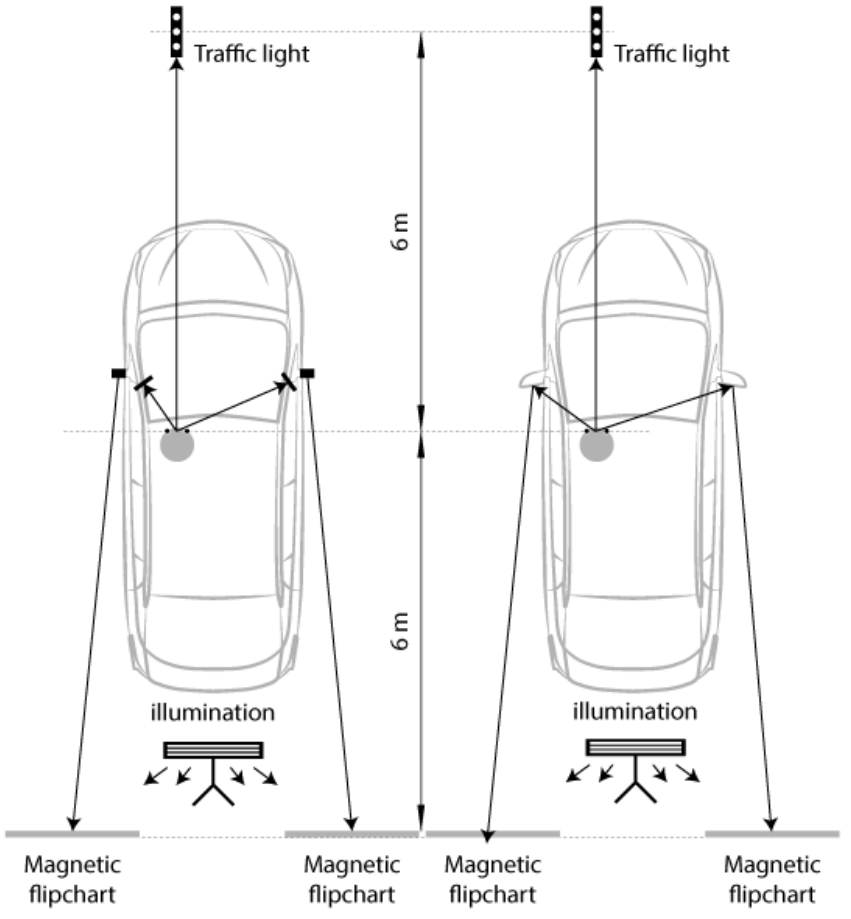


Fig. 4 Testing scheme

Results and discussion

Tobii pro glasses recorded not only eye movement and gaze fixation, but also the voice of participants. Through this audio file using Shotcut video editor, the exact time needed for the participants to recognize the words was extracted. The exact time needed for each word was extracted for both conventional mirrors and digital side mirrors (left and right side). The average time needed for left and right side conventional and digital side mirrors can be seen below in Table 2.

The average time needed for all participants (n = 54) for conventional mirror was 1.155 s (left side) and 1.297 s (right side); and for digital side mirrors was 1.216 s (left side) and 1.394 s (right side). The difference between the left and right mirrors can be perceived

Table 2 Average values of times required for accommodation for specific types of mirrors

n = 54	Left (conventional)	Left (digital)	Right (conventional)	Right (digital)
Average time (s)	1.155	1.216	1.297	1.394
Delta time (s)	0.061		0.098	
Delta time (%)	5.1%		7.2%	

Table 3 Wilcoxon paired test of the difference of the left digital and conventional mirror

Number of respondents	T	Z	*p*-value
54	481.5000	2.07154	0.038309

Table 4 Values of the distances travelled by the vehicle in average time difference

Speed (km·h^{-1})	Speed (m·s^{-1})	Difference in the distance passed when reading the left mirror (m)	Difference in the distance passed when reading the right mirror (m)
130	36.11	2.203	3.539
90	25.00	1.525	2.450
50	13.89	0.847	1.361

as the time required to turn the head to the right, where a larger angular head movement is required. The difference between the conventional and digital mirrors (left = 0.061 s; right = 0.098 s, respectively) can be perceived as the time required for the accommodation of eyes from the conventional mirror to digital displays, as can be seen in Table 2.

According to Shapiro-Wilk test (Cramér, 1946) (Fig. 5), the time differences for the left side mirrors do not have a normal distribution; therefore, it was not possible to use the *t*-test to verify statistical significance. Therefore, the non-parametric Wilcoxon paired test was used; its results are shown in Table 3. Based on these values, the null variant can be rejected and it can be stated that the results are statistically significant.

The normality of distribution was again verified using Shapiro-Wilk test for the measurement results obtained for the right rear-view mirrors. From the distribution shown in Fig. 6, it can be seen that recorded data has a normal distribution ($p = 0.139$). It was therefore possible to use the Student *t*-test to evaluate the results. From the Student t-test, we gained $p = 0.027$, which is less than 0.05, thus confirming this is a statistically significant difference at the 95% confidence level.

The mentioned differences in the times required for accommodation may seem relatively negligible, but if this difference is converted into metres travelled, depending on the speed of the vehicle, it is already a substantial difference, as can be seen in Table 4. The difference is most noticeable at a cruising speed of 130 km·h^{-1}, which is the highest speed limit on a motorway in most countries in Europe (Elvik, 2005). In the left rear-view mirror, it is 2.203 m, and in the right mirror, it is even 3.539 m, a distance that can play a significant role in terms of traffic safety. If the delay caused by the digital mirror technology itself is also added, the total can be more than double the distance, which can be equal to the length of a passenger car.

One relative contradiction can be perceived in the results. The effort spent on accommodation is lower with the right mirror than with the left one due to approximately twice the distance of the focusing point; therefore, the measured difference time should also be shorter. However, this contradicts the results achieved. An explanation can be found in the time needed to turn the head, which is also

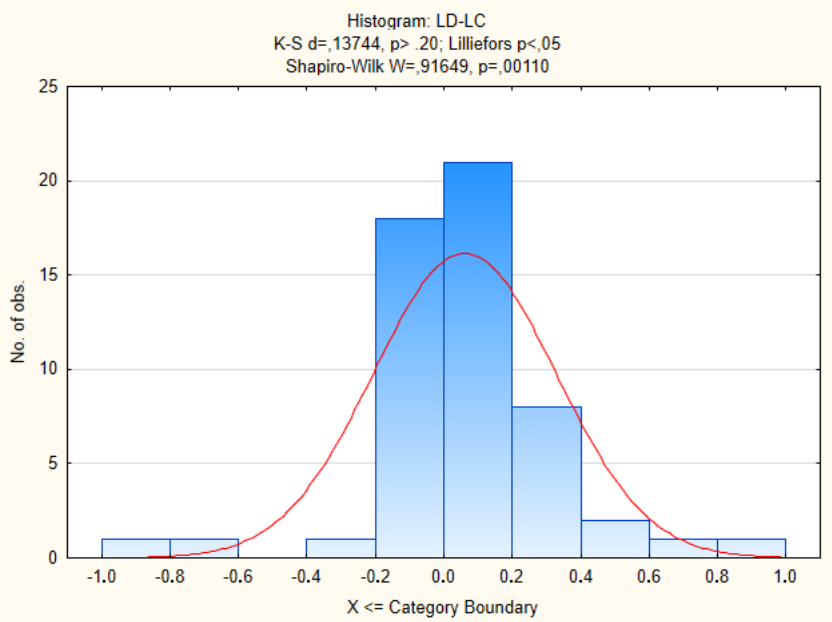


Fig. 5 Shapiro-Wilk test of normality for the left-side mirrors

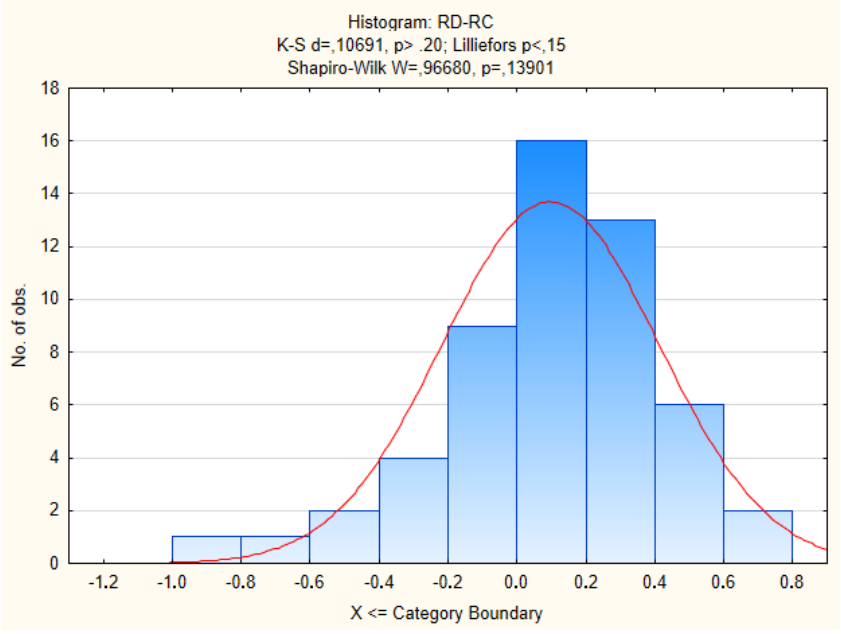


Fig. 6 Shapiro-Wilk test of normality for the right-side mirrors

included in the overall measurement. If the times needed to turn the head left or right are subtracted from each other, the value of 0.037 s comes out to the disadvantage of the right mirror. Theoretically, this value should come out in favour of the left mirror due to the mechanism of accommodation, but this difference represents the time the respondent needs to orientate himself in space and find the right rear-view mirror. The image in the left mirror is completely perceived by respondents' partial periphery. However, these time differences, caused by head rotation and orientation in space, do not play a role in the assessment of the accommodation difference between the conventional and digital mirror, as their influence negates each other.

Dependence of reading speed on gender

In case of the dependence of difference in achieved times on gender, the normality of the distribution of results was verified using Shapiro-Wilk test and it was found that in all cases, it was not a normal distribution. Therefore, non-parametric Kolmogor–Smirnov test was chosen for the statistical evaluation of results (Acock and Stavig, 1979).

Based on the values shown in Table 5, most of the differences between conventional and digital mirrors depending on gender are statistically insignificant, so it can be concluded that gender does not affect the difference in the speed of accommodation for conventional or digital mirrors. The only statistically significant dependence between women and men were revealed in the difference in reading times between conventional and digital mirrors on the left side. In this case, women achieved statistically significant results in comparison with men. The explanation for this difference can be explained with the generally more responsible approach of women to driving a vehicle, where they are significantly more alert and at the same time careful (Mateos-Granados et al., 2021).

Dependence of reading speed on age

Linear regression was used to test the dependence of reading speed on age, but no statistically significant dependence was found. Other statistical methods were used to verify the results, but none of them confirmed the statistical dependence either. It is evident that in order to achieve sufficiently significant statistical deviations, the sample of respondents was not sufficiently heterogeneous in terms of age. A significant limitation of ability to accommodate occurs approximately after the age of 40, when the phenomenon known as presbyopia begins to manifest significantly (Glasser and Campbell, 1999). To confirm this dependence, it would be necessary to create a sample of respondents with a higher average age. However, this was not possible in the given organizational conditions.

Limitations of the study

The authors wish to declare that they are aware of certain limitations of this study, which are mainly caused by measurement conditions. It is evident that laboratory conditions and static testing when the vehicle is not in motion can play a role in the

Table 5 Statistical data of Kolmogorov-Smirnov test for individual rear-view mirrors, divided by gender

Type	*p*-value	Average man (s)	Average woman (s)	Standard deviation man (s)	Standard deviation woman (s)
LC	*P* >0.1	1.157	1.148	0.316	0.233
RC	*P* >0.1	1.223	1.195	0.280	0.242
LD	*P* >0.1	1.299	1.288	0.403	0.288
RD	*P* >0.1	1.436	1.285	0.347	0.285
LD-LC	*P* >0.1	0.066	0.047	0.303	0.135
RD-RC	*P*< 0.025	0.136	-0.003	0.343	0.196

LC – left conventional mirror; RC – right conventional mirror; LD – left digital mirror; RD – right digital mirror; LD-LC – difference between left conventional and left digital mirrors; RD-RC – difference between right conventional and right digital mirrors

mirror reading process. Important factors that were not simulated in laboratory conditions for operational and safety reasons are, for example, variable external lighting, variable meteorological conditions, or, possibly, vibrations due to the movement of the vehicle on an imperfectly level road. However, it is evident that real conditions would further deepen the above-mentioned differences between conventional and digital mirrors, which is also mentioned by another study dealing with the usability of digital mirrors in passenger vehicles (Babu et al., 2022).

The use of digital mirrors in vehicles is still a relatively new area of research and much work needs to be done to understand their potential benefits and limitations. Our study did not focus on users with disabilities, but we understand this direction has great potential. Below, we list possible directions for further research from our perspective, but we have not yet found a sufficient overview of scientific resources.

Some published studies (Large et al., 2016; Babu et al., 2022) report both the positives and negatives of using digital rear-view mirrors. However, in their studies, they only used the conventional display of information provided by the camera. However, the image provided could be enhanced. Digital side mirrors can also incorporate features such as augmented reality overlays and object detection, which can help drivers with visual impairments to navigate more safely and confidently. For example, an augmented reality overlay could provide information about nearby objects, such as their distance and speed. In contrast, object detection technology could alert the driver to potential hazards such as pedestrians or other vehicles.

It is also an integral fact that digital mirrors within vehicles may improve aerodynamics and the field of view (Pampel et al., 2020). This feature can slightly help all drivers but is not targeted primarily at drivers with visual impairments.

Additionally, digital side mirrors have the potential to be integrated into other advanced driver assistance systems, such as lane departure warnings and blind spot monitoring (Adrian et al., 2017) to provide a more comprehensive view of the driving environment.

A study conducted on Lexus and Audi eTron vehicles (Schkreba, 2020; Capparella, 2018) found that a digital side mirror maintains visibility that is equal to or greater than an optical mirror – even when the lens is twice or dirtier than the glass surface of the mirror.

Conclusion

The above results confirmed statistically significant differences in the speed of accommodation when reading data from conventional and digital mirrors. It has been shown that the use of digital mirror technology can have a direct negative effect on road safety, especially in combination with other negative effects given by the technical nature of the technology under investigation, such as image latency in digital displays. These negative phenomena can further be combined with the driver´s attitude, given by his cognitive functions (Babu et al., 2022).

In terms of the input data, statistical dependence was confirmed in the difference in reading information for the left rear-view mirrors, where it was shown that women were able to read information significantly faster than men. The explanation for this difference was given above. Although further statistical dependence could not be demonstrated, it is necessary to point out that further testing in this area using a significantly more heterogeneous group in terms of age of respondents would probably bring new knowledge, given the expected deterioration of accommodation amplitude in patients over 40 years of age (Glasser and Campbell, 1999).

Data collection and statistical processing were carried out in high quality and were verified as valid. The results can be used for further research or development of manufacturing solutions. The obtained results and the knowledge derived from them can be used in general for all types of vehicles, such as trucks or agricultural machines. The study does not aim at an unequivocal rejection of the researched technology, but the authors consider it important to mention all the possible identified negative aspects that could influence the use of this technology and thus have an impact on road traffic safety.

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