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ORIGINAL ARTICLE

Visual guidelines integration for automotive head-up displays interfaces

J. Alejandro Betancur[1] · Hector Vargas[1] · Carlos Sanchez[1] · Frederic Merienne[2]

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Abstract

Designing automotive Head-Up Displays (HUD) interfaces requires careful consideration of visual guidelines to ensure safety. While specific safety guidelines exist, a general set of visual guidelines has not yet been established. Therefore, this research presents a comprehensive methodology to derive overall visual guidelines designed to project warnings on HUD interfaces. To this end, the present work focused on asking 20 test subjects for driving in various scenarios, while visual stimuli were projected on a specific HUD system, identifying drivers' behavior patterns and reaction trends. These visual stimuli were based on already tested visual guidelines. The results obtained from this methodology show that it is possible to integrate all previous qualitative and quantitative visual guidelines, allowing for drivers faster reactions and better recognition of warnings. This integration enables determining the most and the least suitable way for presenting information in a specific HUD system concerning identification mistakes and reaction times. Moreover, these findings imply the feasibility of anticipating a driver's comprehension of warnings in HUD interfaces.

Keywords Head-up display · Visual guidelines · Human–machine interface

1 Introduction

Currently, there are various technologies in the automotive industry where interface efficiency links to the fast visual stimuli identification. These technologies seek to prevent distractions while driving, using elements such as automotive instrument clusters, HUDs, head-down displays, and others [1, 2]. The HUD system is a device that situates information within the driver's view through the windshield; then, the primary advantage of a HUD lies in presenting relevant information inside the driver's visual field, reducing distractions, and minimizing gaze diversion to a minimum [3, 4]. However, this benefit could be attenuated by implementing HUD interfaces that produce an uncomfortable user experience.

On the other hand, the HUD systems considered in this context are optical see-through systems categorized into two main visual interface groups, as illustrated in Fig. 1: (1) presenting information about the driving environment combined with pre-structured data, engaging drivers through a series of visual stimuli and artificial scenes, and (2) conveying state information (e.g., vehicle speed, engine RPM, fuel level, trip information, etc.), status information (e.g., ACC on/off, the airbag on/off, lights on/off, etc.), alerts (incoming phone calls, upcoming locations, etc.), and warnings (imminent hazard mitigation and hazard avoidance situations) [5, 6]. The latter aspect of the second interface group serves as the central focus of the research work at hand. Therefore, this work proposes a methodological procedure for designing interfaces in automotive HUD systems for presenting warnings. The aim is to identify combinations of quantitative and qualitative visual guidelines from previous studies that can positively or negatively impact the driving performance.

✉ J. Alejandro Betancur
jose.betancur@docentes.umb.edu.co

Hector Vargas
hector.vargas@docentes.umb.edu.co

Carlos Sanchez
carlos.sanchez@umb.edu.co

Frederic Merienne
frederic.merienne@ensam.eu

[1] Vicerrectoría de Investigación, Universidad Manuela Beltrán, Avenida Circunvalar No. 60-00, 110231 Bogotá, Colombia

[2] Arts Et Metiers Institute of Technology, LISPEN, HESAM Université, UBFC, 71100 Chalon-Sur-Saône, France

Fig. 1 HUD functional application [7]

2 Visual guidelines in HUDs

From a quantitative perspective, researchers have identified optimal conditions for the placement of virtual images generated by HUD systems. It is widely acknowledged that the most effective position lies within the drivers' line of sight and 10 degrees of eccentricity [8–11]. Outside of this range, the HUD information is widely refused by drivers, mainly because they must move their head to identify the displayed information. Additionally, studies emphasize the importance of limiting the time spent glancing from the road to the HUD system to less than 2 s to mitigate the risk of traffic accidents [12, 13]. Furthermore, investigations have demonstrated that far away images imply faster eye accommodation responses, which is directly related to better image recognition and reduced reaction times [14–17].

On the other hand, various studies have explored auditory stimuli configurations for handling HUD functionalities [18, 19]. It has demonstrated that audio-visual HUD system configurations enable drivers to maintain their attention on the road rather than on HUDs, proving to be particularly valuable for driving situations demanding full visual attention. Similarly, these audio-visual configurations have shown the ease of using HUD interfaces in less time and with reduced physical effort, as proposed by different research studies [20–22].

There are studies that cover broadly the usage of different colors in automotive HUD systems [23–28]. For instance, from a scientific approach it is strongly recommended to avoid red and blue color usage at night [23], and also, among the pink, purple, red, orange, brown, blue, green and yellow colors, the last three were more perceptually recognizable and produced slightly lower response times when performing symbol and text tasks; however, yellow color performed significantly better for symbol tasks than the other ones, but it produced the most mistakes quantity during text tasks [25]. Moreover, from the qualitative point of view, regarding the human sensations about colors in HUD systems, the orange, green and blue colors were tested, being the first two ones oriented toward a modern feeling, and the final one to an ancient feeling [26, 29]. On the other hand, from the industrial point of view it has been proposed full-based green color interfaces for information projected under typical driving circumstances, and red warnings for defining extreme operational conditions [27–29].

According to the above, by applying conjointly two or more of the previously mentioned guidelines it is possible to find other ones, which is a necessary step for enhancing the current state of the art in HUD interfaces. In this way, the next section describes how a proposed instrumental setup and data acquisition procedure could be applied to test subjects in order to obtain identification trends; then, in Sect. 4 these trends are analyzed in order to propose basic visual guidelines. Finally, in Sect. 5 and 6 further research steps for applying these visual guidelines and conclusions are presented respectively.

3 Methods

In order to explore and validate the interaction among the previously indicated visual guidelines in HUDs, the following main steps have been proposed:

Regarding the current literature, in this article we present our findings about how to design a HUD visual interface in terms of warnings identification; therefore, our hypothesis is that it is possible to integrate and evaluate the previous

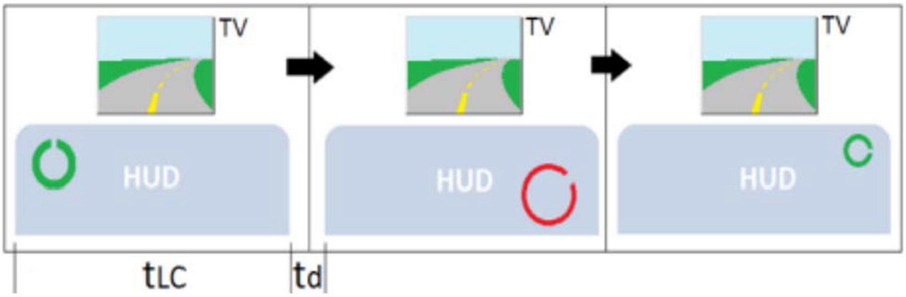

Fig. 2 Schematic view of the proposed experiment (tLC: time interval in which a LC ring is displayed; td: time interval between two LC rings)

quantitative and qualitative HUD visual guidelines, allowing for drivers faster reactions and better recognition of warnings [6]. This hypothesis is also based on the results presented by Pečečnik et al. [8] and Li et al. [30] that expose how different HUD visual interfaces could impact on the driver performance. In that regard, for solving the previous hypothesis this study proposed a methodology, trying to answer following the two main research questions:

- What is the most suitable and the less suitable visual configuration for identifying correctly a warning while driving?
- What is the most suitable and the less suitable visual configuration for identifying quickly a visual warning while driving?

3.1 Technical description of the experiment.

The proposed experiment consists in a set of Landolt C rings[1] (LC) that were projected on a specific HUD system, while changing their design factors as exposition times, delay times, sizes, positions, colors and orientations. Then, the test subjects were asked to press a button on the steering wheel when a right oriented LC ring was projected in the HUD system; simultaneously they were also asked to drive a car[2] several times in a simulated scenario as fast as possible. This scenario consists on a test track[3] especially configured for making the car slipping drastically, and consequently making the test subjects to be always aware of the driving context, as in a hazard situation; the above is shown schematically in Fig. 2, where some main test variables are exposed.

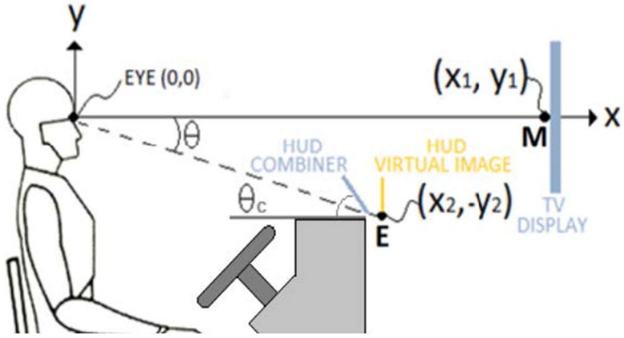

Fig. 3 Schematic view of the proposed testing bench. M: middle point of the TV display, which coincides with the drivers' sight line. E: virtual image position of the proposed HUD system. At this point the combiner is also placed. θ: maximum eccentricity viewing angle that subtends all the HUD virtual image = 10°. θc: combiner inclination angle = 45°. (x_1, y_1): digital screen display coordinates = (6.0, 0.0 m). (x_2, − y_2): HUD virtual image coordinates, these distances are based on the driver's Depth Of Field (DOF) = (2.3, − 0.4 m). This is a design parameter proposed in literature by Helander et al. [31], regarding that for an emmetropic adult human looking at the optical infinity, his depth of focus is 0.43D (2.3 m) [32]

Then, the proposed experiment was applied 12.960 times, changing the above-mentioned design factors; in this way, obtaining 648 responses for every test subject and 77.760 total registers. All data is available upon request.

According to Fig. 2, the proposed testing bench involves 2 main components, a TV display and a HUD combiner. The position in which these must be placed, and its constructive parameters are indicated in Fig. 3.

This testing bench is focused on reaching the same accommodation effort for virtual and real driving situations when moving between 2 planes (HUD image and TV scenario),

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[1] The LC ring is an optotype proposed by Edmund Landolt, which is focused on the visual acuity evaluation.

[2] Sport utility vehicle: mass = 1000 kg, motor revolution per minute (min-max) = 3.000–10.000, differential ratio = 3.67, front brake torque = 6000 Nm, back brake torque = 5500 Nm, wheel mass (4 wheels) = 23 kg, wheel radius = 0.4 m, dynamic friction (wheel-ground) = 0.07, static friction (wheel-ground) = 0.9.

[3] lane track (11.6 m wide) arranged as follows: straight line of 1119.63 m, curve of radius 162.23 m, straight line of 378.67 m, curve of radius 104.78 m, straight line of 1811.40 m, 3 consecutive curves of radius 108.90 m, 209.63 m, 209.63 m respectively, straight line of 198.58 m, 4 consecutive curves all of radius 211.60 m, straight line of 176.09 m, 2 consecutive curves of radius 213.68 m and 207.66 m respectively (downhill), straight line of 176.09 m, 3 consecutive curves of radius 206.58 m, 206.58 m, 190.24 m respectively (uphill). Good visibility conditions without traffic, but some obstacles were randomly included on the track, looking for avoiding learning effects as much as possible.

Footnote 3 continued

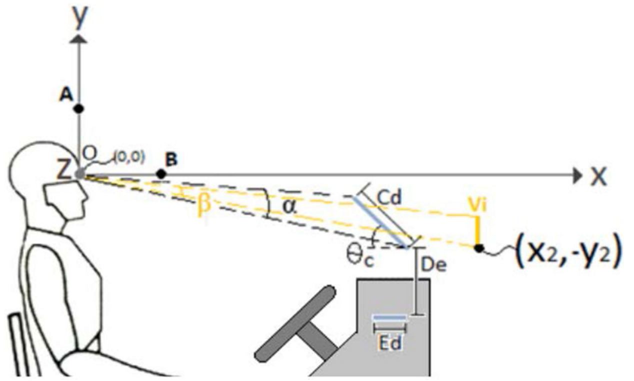

Fig. 4 Schematic configuration and main design parameters to be considered in the MIR-HUD architecture.A and B: limit driver's eye positions on the Y and X axes respectively. θc: combiner inclination angle. α: optical system field of view (α_{xy}, α_{xz}). β: minimum virtual image field of view (β_{xy}, β_{xz}). Ed: emissive display dimensions (Ed_{xy}, Ed_{xz}). Cd: combiner dimensions (Cd_{xy}, Cd_{xz}). De: combiner-emissive display distance. Vi: virtual image

without overcoming the driver DOF; this testing bench architecture is known as MIR-HUD, and some of their main geometric considerations are shown by Fig. 4.

Regarding Fig. 4, the main scope of this section is exposing the combiner dimensions that always make α bigger than β for a driver position range and a θc value. In this way, the α angle can be considered as the Field Of View (FOV) of the optical system, and the β angle as the FOV needed to view all the virtual image extensions. Consequently, the ratio between them could be understood as the eye-box performance, which is the geometrical space where the driver can move his/her head viewing the whole HUD virtual image [33, 34], and it is represented as a cube containing the head, whose boundary points A and B are shown in Fig. 4.

The points A and B must be defined ensuring that test subject will always be able to look at the HUD virtual image even if small head movements are done while developing the proposed test; consequently, ± 0.05 m were defined as a limit for the driver's eye movements [35], this value was also applied to limit driver's eye positions for the Z axis, which were defined as Z_J and $-Z_J$; On the other hand, De was settled to zero, trying to make the HUD virtual image as bright as possible. Additionally, the driver perception is also affected by the physical properties of the proposed HUD combiner, which is going to be defined in the next section.

3.1.1 Technical specifications

The reflection of the combiner makes change for a light ray (that impinges on a surface with a θc inclination), the portion of light reflected toward the driver; consequently, the material of the combiner varies its reflectance values depending on the color projected on it, making the HUD virtual image fluctuates in terms of luminance, which at the same time could influence the driver identification responses [29, 36–38]. Therefore, the reflectance (and also the transmittance) of the proposed combiner (*material I*, thickness 2.15 ± 0.05 mm) were measured,[4] as shown in Fig. 5.

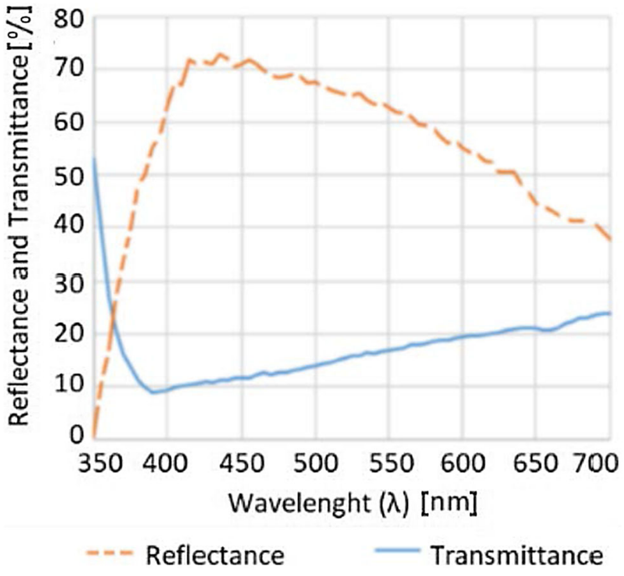

Fig. 5 Reflectance and transmittance spectrum of the *material I*

Once the optic characteristics of the *material I* were identified, as proposed previously, for constructive reasons the θc angle was settled at 45° and the y_A and the z_J variables were fixed both to 0.05 m, which are the first steps for proposing the combiner dimensions; therefore, for the x,y plane, these dimensions consists on finding the C point, which is produced when $\underline{AD}$ intersects $\underline{FE}$, as shown in Fig. 6 and Eqs. (1) and (2).

$$x_3 = \frac{-0.05 - x_2 \cdot \tan(-\theta_c) - y_2}{\left(\frac{-y_2+Ed_{xy}-0.05}{x_2} - \tan(-\theta_c)\right)} \qquad (1)$$

$$y_3 = \left(\frac{-y_2 + Ed_{xy} - 0.05}{x_2}\right)x_3 + 0.05 \qquad (2)$$

For determining the combiner dimension in the x,y plane it is necessary to identify the distance between points (x_2, $-y_2$) and (x_3, $-y_3$). On the other hand, in Fig. 6b the lateral combiner dimension consists on finding the point K, for which it is possible to replace Eq. (1) in the linear equation described by $\underline{JL}$; however, this is just applicable when the point $Z_j > Ed_{xz}/2$, in this case the Z_j value is too small and the above do not proceed, but $Z_4 = Ed_{xz}/2$. At this point, the main parameters of the proposed instrumental setup are fully described by Table 1 and Fig. 6.

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[4] The reflectance of the *material I* was analyzed for the visible spectrum, in order to consider the 5 different colors suggested in Sect. 3.3.

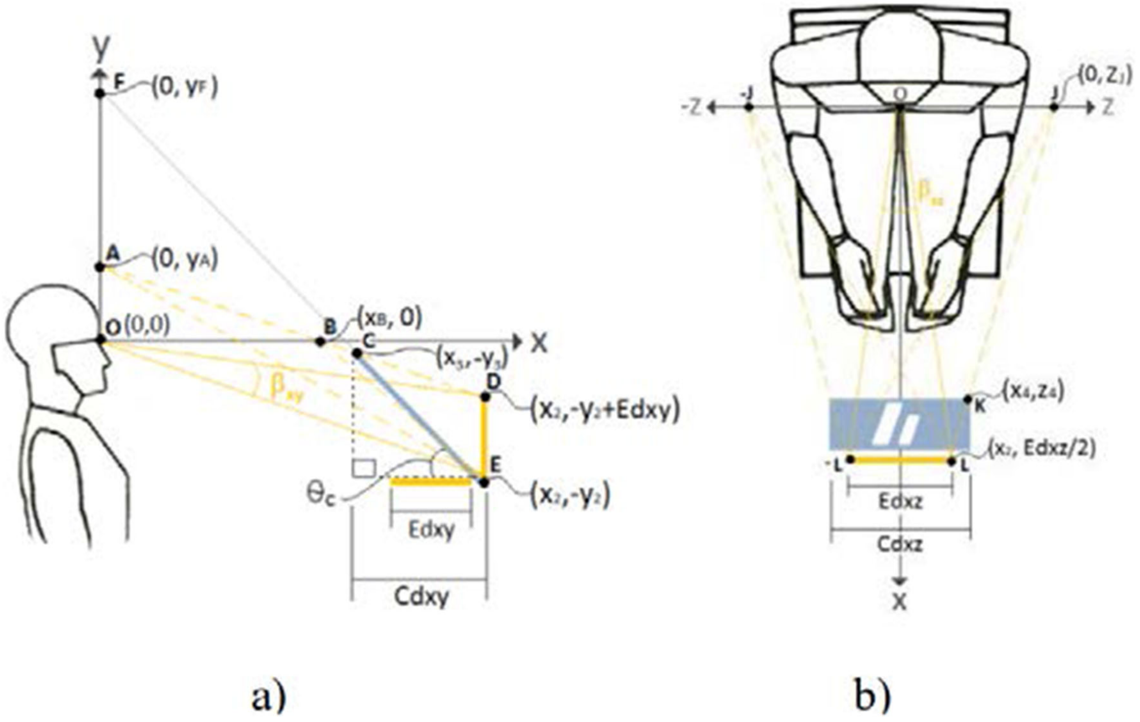

Fig. 6 **a** Detailed analysis for the eye-box in the x,y plane. **b** Detailed analysis for the eye-box in the x,z plane

Table 1 Values for the HUD testing bench

Concept group	Parameter	Value
Input: emissive display dimensions and combiner inclination	Edxy	0.070 m
	Edxz	0.126 m
	θc	45°
Output: main points definition	A	(0, 0.05, 0 m)
	B	(0.059, 0, 0 m)
	C	(2.17, − 0.70, 0 m)
	D	(2.3, − 0.75, 0 m)
	E	(2.3, − 0.83, 0 m)
	F	(0, 1.47, 0 m)
	J	(0, 0, 0.05 m)
	K	(2.17, 0, 0.07 m)
	L	(2.3, 0, 0.07 m)
	M	(6.0, 0, 0 m)
Output: combiner dimensions	Cdxy	0.170 m
	Cdxz	0.140 m

3.2 Test subjects selection

Some procedures were developed in order to evaluate the visual qualities of all test subjects. In this sense, the Freiburg visual test software for Visual Acuity[5] (VA) was implemented [39], in which test subjects were prompted to identify (during 5 min) different LC rings configurations, with different orientations and sizes. In this way, the above procedure was also useful for practicing the LC ring identification test included in the proposed HUD system.

For developing the above-mentioned procedure a PC-screen placed at 600 cm from the test subjects' eyes was implemented, which is related to the LC ring size proposed by the EN-ISO norm 8596; moreover, the PC-screen resolution was also considered by the proposed Freiburg vision test software, in order to avoid any aliasing effect; also, the same luminance source proposed in Sect. 3.1.1 was used for developing the above-mentioned test, mainly because the VA values vary according to the intensity of the retinal illumination, being directly proportional [33].

Regarding the above, for this study 20 test subjects were considered (9 males and 11 females), from 18 to 35 years old (mean = 21.76, standard deviation = 4.47). All test subjects had normal or corrected-to-normal sight, i.e. similar VA (Right eye: mean = 1.071, Right standard deviation = 0.412, Left eye: mean = 1.032, Left standard deviation = 0.416). Also, all test subjects were right-handed, regarding that some studies support differences in terms of reaction times between right- and left-handed subjects [40, 41].

Finally, during the proposed experiments all test subjects were naïve about the scope of the obtained results; also, every test subject was provided with a written consent to participate in these experiments, declaring s/he has no history of psychiatric, neurological or dramatic ophthalmological illness.

3.3 Data acquisition procedure

According to the procedure detailed in Sect. 3.1, some dependent and independent variables were defined, which are detailed here below.

3.3.1 Dependent variables

Driver reaction time: it is the time a test subject requires for correctly identifying a LC ring.

Detection type: the LC rings identification can be classified according to Table 2.

Table 2 Possibilities for all LC ring identifications

Possibilities	The test subject pressed the button	The test subject does not press the button
The right-oriented LC ring appears	Hit (Hi): The LC ring appears and the test subject presses the button	Missing (Mi): the LC ring appears but the test subject does not press the button
The right-oriented LC ring does not appear	False-alarm (Fa): the LC ring does not appear but the test subject presses the button	Correct Rejection (Cr): the LC does not appear and the test subject does not press the button

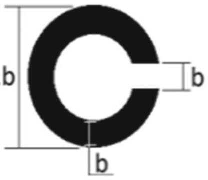

Fig. 7 LC ring dimensions

3.3.2 Independent variables

3.3.2.1 LC ring size (LCsize) 5, 10, 15 mm. According to the latest norms ISO 2575 and DIN-EN ISO 15008 the minimum and optimal character heights at 3 m for HUD virtual images are 10.47 and 17.45 mm respectively. In this way, regarding X2=2.3 m instead of 3 m, the minimum and optimal character heights would be 8.02 mm and 13.37 mm respectively. On the other hand, according to the USA Department of Defense [43] the height for non-alphanumeric characters in HUD systems should be not less than 0.566°, which means that for X2=2.3 m the LC rings should have at least 22 mm of height. According to the above, the proposed values were considered based on an exploration of the previously mentioned values, taking as threshold the average VA value of the proposed test subjects. Regarding the above, all LC ring dimensions can be defined as shown in Fig. 7, where the LCsize is the 5.b distance.

3.3.2.2 LC ring position (LCposition) 9 levels. The LCposition indicates, for the HUD virtual image, the positions in which the LC rings are going to be displayed; therefore, for this case study 9 positions were proposed in order to cover most of the HUD virtual image extension, as shown by Fig. 8.

3.3.2.3 LC ring exposition time (tLC) 0.2, 0.8, 1.4, 2 sec. These exposition times were defined according to Ma et al. [12] and Liu and Wen [13] for which the maximum time of

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[5] VA is defined in Eq. (3) as proposed by Colenbrander [42]:

$$\mathrm{VA} = 1/\alpha[\text{arc min}] \tag{3}$$

where α is the angle that the gap size (b value, see Fig. 7) of the LC rings subtends at the test subjects' eyes.

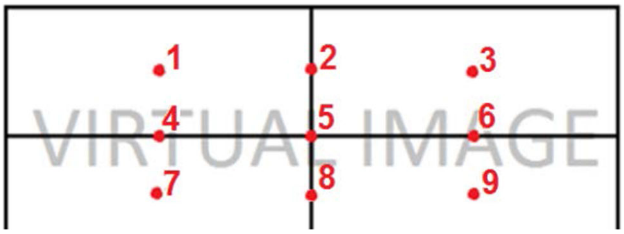

Fig. 8 LC ring positions

glances from the road to a HUD system must be less than 2 seconds, looking for avoiding negative effects on the driving performance; but also, the lowest value of this exposition time must be higher than the lowest value of the mean visual reaction time in humans, i.e. 0.180–0.200 sec [44]; thus, the proposed exploration takes the previous level + 0.6 sec, beginning with the shortest exposition time until the highest one.

3.3.2.4 LC ring delay time (td) 0, 0.4, 0.8, 1.2 sec. These values were proposed as an exploration based on the Perception Of Simultaneity (POS) concept, which indicates the minimal time interval between two stimuli for a human to be able to discriminate between these [45]. Regarding the above, according to Artieda et al. [46] and Green et al. [47] the discrimination threshold for visual stimuli is 68.7 ± 5.1 milliseconds. Therefore, this variable explores the discrimination threshold 0, 6, 12 and 18 times.

3.3.2.5 LC ring colour (LCcolor) Red (255, 0, 0), Green (R143 G195 B31), Blue (R139 G188 B229), Orange (R248 G182 B45) and White (R255 G255 B255). These were considered based on the results obtained by Park and Park [24], Merenda et al. [25], Smith and Fu [26] and Brown et al. [27], which proposed these colors for their HUD interfaces.

3.3.2.6 LC ring orientation (LCorientation) 6 levels. These are the opportunities the test subjects have for identifying the right-oriented LC rings among all different LC orientations, which means the replicas of the proposed experiment. Therefore, 3 different orientations of the LC rings were displayed, for every combination among the above-mentioned factors, after randomly selected among eight possibilities: 4 horizontal orientations (3 right, 1 left) and 2 diagonal orientations (right-up, right-down).

4 Data analysis & discussion

4.1 Driving skills analysis

As mentioned in Sect. 3.1 all test subjects were prompted to drive a specific track as fast as possible, then, their lap times were recorded and compared for male and female groups. The original data was divided by gender since results have different frequency distributions for men and women. Lap times were compared between test subjects within each group by using a Kruskal Wallis test. Results show that the male test subjects group do not have significant differences between any pair of subjects, even though the p-value of Kruskal Wallis test turned out to be lower than 0.05 (p-value = 0.032); the above is explained since the Mann Whitney pairwise comparisons corrected by Bonferroni show that there are not significant differences between any pair of the male test subjects (p-values > 0.05, for all pairs).

Furthermore, the female group showed very different frequency distributions among test subjects, which could be explained by the wide range of driving experience presented in women selected for this study. The above did not allow the validation of homogeneity of variance assumption for Kruskal Wallis test, and therefore the Friedman test was used to analyze female test subjects lap times. Even though Friedman test showed a p-value lower than 0.05 (p-value = 6,97E-05), the Wilcoxon pairwise comparisons corrected by Bonferroni show that the lap times do not have significant differences between any pair of female subjects (p-values > 0.05, for all pairs).

4.2 Categorical responses analysis

According to the set of explanatory variables depicted in Sect. 3.3, a bivariate Logistic Regression (LR) analysis was implemented for predicting whether an element can belong or not to a specific dichotomous classification. Therefore, regarding the Table 2 this dichotomous classification was focused on whether the displayed LC rings were correctly identified by the proposed test subjects when it appeared in the right oriented direction.

For the LR data, the homogeneity of variance does not need to be satisfied, and also the data residuals do not need to be normally distributed, but there must be independence among them. The above is accomplished by randomly running all treatments, in order to guarantee there is no correlation among the residuals and the order in which the treatments were run during the experiment; then, the independence among the data was verified throughout the Runs test (p-value = 0.22 > 0.05).

For training the LR model 846 treatments were selected randomly for each type of response (1692 treatments overall). This number represents nearly 50 and 17.8% of total observations for Hi and Mi respectively. Then, the training database represents the 26.11% of the original observations related to the Hi and Mi responses, which means the model was tested on the remaining 73.88%. The resultant model is described below in Eq. (4).

Table 3 Correct classification percentages for Hi and Mi responses

Observed answers	Predicted answers		Correct Classification Percentage
	Hi	Mi	
Hi	1342	350	79.31
Mi	1358	3430	71.64

$$\log it(\pi i) = \log\left(\frac{\pi i}{1-\pi i}\right) = 1.517 - 25.58 * t_{LC(0.2)} - 2.131 * t_{LC(0.8)} - 1.013 * t_{LC(1.4)} - 0.773 * LC_{size(5)} \quad (4)$$

The proposed LR model explains 45.9% (Nagelkerke, R^2) of the variation in the dependent variables. As mentioned above, the obtained model was tested on the database selected for this purpose, showing a correct classification percentage over 70% for each type or response, as shown in Table 3.

According to the above, the obtained model incorrectly classifies 1708 observations, which represents 26.36% of the total database. This means that correct classifications represent 73.64% of the database, suggesting that the test subjects´ behavior in terms of LC ring identification is related to the variables mentioned in the proposed LR model.

Furthermore, according to the obtained model, increasing values of the tLC seem to be associated with an increase in the likelihood of generating a Hi response (p-value = 0.000 < 0.05), for example the lowest tLC level (i.e. 0.2 seg) augments the odds ratio of Mi responses to 1.29E11/1, meaning that information presented during 0.2 s or less has an outstanding chance to be missed by drivers. On the other hand, a tLC of 0.8 s has an odd ratio for Mi responses of 8.4/1, and information presented during 1.4 s produce an odd ratio of 2.7/1; Also, presenting the LC ring with the smallest size (5 mm, b = 1 mm), elevates the missed response odds ratio to 2.16/1.

Therefore, although these levels are analyzed separately, all of them show a tendency to reduce the possibilities of generating a Hi response. Hence, these results suggest that it is not recommendable to present symbols with short exposition times, and also it is strongly suggested to avoid displaying these for less than 0.2 s, as users will not notice important information. The same problem is triggered by the smallest size of the proposed LC rings. Additionally, even if all levels of the factors here considered are all categorical, there is no information in literature for supposing that lower or higher levels for tLC and LCsize are not going to follow the identification trends exposed by Eq. (4).

In the same way, according to the obtained results, neither the positions for displaying the LC rings nor the delay times here explored, are significantly related to the probability of missing the information nor identifying it correctly on time. The above, is strongly related to the results exposed by Tretten et al. [10], Yoo et al. [11] and Ma et al. [12], which found how for the HUD information placed in the area contained by the drivers´ line of sight and 10 eccentricity degrees, there are not significant differences in terms of driving distraction. Also, the exploration here proposed in terms of the delay time is valuable for clarifying how under the experimental conditions previously indicated, the POS concept is not related to presenting warning information on a HUD system.

On the other hand, the obtained results suggest that there are not significant differences among all colors selected for this study. However, as proposed by Alves et al. [28] and Brown et al. [27], there is a stronger usability preference for red color in comparison to green color during hazard situations. Also, for this experiment there were not changes in the driving responses for LC ring sizes equal or higher than 10 mm (b = 2 mm = 0.05°), which differs from results indicated by the USA Department of Defense [43], proposing for non-alphanumeric characters a visual angle not less than 0.566°; however, it must be considered also the type of test subjects and driving environment proposed in that research, being mainly focused on military systems.

Then, from Eq. (4) all possible treatments groups (G) are indicated in Table 4, in which (according to the abovementioned odd ratios) the G1 has an identification Probability (P) of 82.0%, followed by the G2, G7, G8, G5 and the G6 with a Probability (P) of 67.8, 62.3, 43.3, 35.1 and 19.9% respectively; then, the G3 and G4 both have a mathematical P equal to 0%. It must be taken into account that an acceptable identification percentage must be at least 50% or more, which leaves just treatment groups G1, G2 and G7 as viable projection alternatives during common driving situations.

4.3 Numerical responses analysis

According to the Friedman test, some significant differences in terms of reaction time were recognized for the abovementioned G treatments groups (H = 118.202, d.f. = 5, p-value = 0.000 < 0.05). In this sense, throughout the Wilcoxon pairwise comparisons, the significant differences reported in Table 5 were obtained (above the diagonal of zeros). Additionally, looking for more accurate differences between the G groups, the Bonferroni pairwise correction was implemented also in Table 5 (below the diagonal of zeros).

Then, for $p > 50\%$ and the Bonferroni correction data, in terms of reaction times there were not significant differences among the treatments groups G1 (mean = 1.2846 s)—G2 (mean = 1.2553 s) and G2–G7 (mean = 1.1010 s), being G1 the most suitable option for projecting information in the HUD here proposed, and the G7 the lower acceptable one. Next, for $p < 50\%$ there are no significant differences between

Table 4 Probabilities for all considered treatments

Group	Terms indicated in Eq. (4)				
G	1.517	t 0.2	t 0.8	t 1.4	Size 5
1	1	0	0	0	0
2	1	0	0	0	1
3	1	1	0	0	0
4	1	1	0	0	1
5	1	0	1	0	0
6	1	0	1	0	1
7	1	0	0	1	0
8	1	0	0	1	1

Table 5 Obtained pairwise comparisons for the selected treatment groups

G	Selected treatments groups					
	1	2	5	6	7	8
1	0	1	**1, 8E-07**	**1, 8E-07**	0.475	**0.00038**
2	0.991	0	**1, 1E-06**	**7, 7E-07**	0.876	**0, 00580**
5	**1, 2E-08**	**5, 1E-08**	0	1	**1, 1E-07**	**7, 3E-05**
6	**1, 2E-08**	**7, 6E-08**	0.856	0	**3, 8E-08**	**4, 9E-05**
7	**0.03169**	0.058	**5, 77E-07**	**1, 7E-06**	0	**0.006515**
8	**2, 5E-05**	**0.00038**	**0.000746**	**0.00109**	**0.000434**	0

G5 (mean = 0.6312 s) and G6 (mean = 0.6517 s), but G8 (mean = 0.9541 s) is significantly different from G5 and G6. Then, G3 and G4 were not analyzed because the numeric available data were below 300 ms, which according to the signal detection theory it is the minimum time for assuming a valid detection response [48].

In this sense, considering a common driving situation in which a fast acquisition of information throughout a HUD is not a priority ($p > 50\%$), the most and the less suitable way for projecting warnings in the proposed HUD system (under the experimental considerations here established: G1[6] the most suitable way and G6 the less suitable way) is indicated in Table 6.

According to the above, it is possible to identify a strong relation between the P of a G group and the main reaction time associated to it; therefore, a polynomial equation linked to the above-mentioned relation can be proposed, as shown in Fig. 9 and Eq. (5). In this approach the maximum error is 20.6% corresponding to the G5, then 11.2% for the G8, and below 7% for the other G groups. However, this analysis does not allow to precise visual guidelines for other different P values calculated without applying the Eq. (4), being an approximation for exploring other possible visual guidelines.

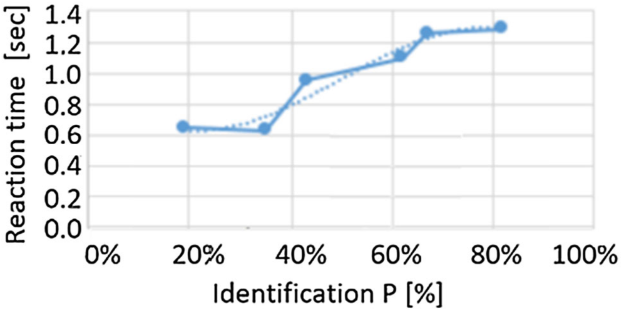

Fig. 9 Reaction time (RT) vs Identification Probability (P)

$$RT\,(x) = -7.5218\,(P)^3 + 11.262\,(P)^2 - 3.8491\,(P) + 1.0137;\;\; R^2 = 0.8947 \qquad (5)$$

5 Perspectives

Currently, we are carrying out validation exercises about the design guidelines shown in the previous section as beneficial for the driver behavior. For this purpose, and according to the setup parameters depicted in the proposed methodology, we have designed a HUD device that is patented in the United

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[6] E.g. the G1 group refers to all the projected warnings using 10 mm and 15 mm of size, with 2 s of exposition time, in any of the positions, delay times, and colors here analyzed.

Fig. 10 Proposed HUD device and interface

Fig. 11 braking warning for the proposed HUD interface

States [49] and whose interface provides visual driving warning, as indicated in Figs. 10 and 11. Then, this validation exercise has shown clear driver identification trends in time mainly for urgent braking warning; and consequently, this warning has been projected using the G1 guideline exposed in Table 6, which exposed the most suitable visual configuration for projecting information in the proposed HUD system.

6 Conclusions

The LR analysis here proposed could be explored in many other different ways, therefore in this research the main LR concepts were exposed for developing a specific and basic oriented case study. In this way some other considerations can be included, as the Cr and Fa responses in a driving context for different types of HUD warnings. On the other hand, the

Table 6 The most suitable and the less suitable visual configuration for projecting information in the proposed HUD system

G	LCsize[mm]	LCposition	tLC	td	LCcolor
1	10, 15	1, …, 9	2.0	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green
2	5	1, …, 9	2.0	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green
7	10, 15	1, …, 9	1.4	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green
8	5	1, …, 9	1.4	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green
5	10, 15	1, …, 9	0.8	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green
6	5	1, …, 9	0.8	0.1, 0.4, 0.8, 1.2	Yellow, blue, orange, red, green

proposed G groups are gathered between 180 and 360 treatments; therefore, reporting all significant differences inside the G groups is not possible due to the final length of this paper. However, the proposed analysis gives statistical suggestions for exploring more specific visual configurations of warnings in HUDs. Therefore, this approach just indicates a basic statistical method for estimating significant differences among the proposed G groups.

Under the experimental considerations here proposed, the developed methodology is useful for determining how to project information in HUD systems according to a specific hazard situation. For instance, an Advanced Driver Assistance System (ADAS) could calculate that less than 1 s last for a very probable crash (i.e. $p > 80\%$), and therefore, it could decide to project information in the HUD with a low P, looking for suggesting a driving action in less than 1 s, as take place in groups G5, G6 and G8 (even if drivers could not identify this information); in this way, for these last ones groups the exposition time is less than in the other ones, and therefore even if its associated P are lower, drivers will have more identification opportunities.

However, it must be considered that all reaction time data obtained from the proposed experiment are not perfectly related throughout a mathematical equation, but these tend to be also related to the individual response capacity [50–52]. This means that even if the proposed LR model can predict (with 73% of accuracy) whether drivers will identify a specific visual stimulus, once it is identified, the reaction time does not always seem to be related to the way information is presented in the HUD, but to the drivers' reaction capabilities [53, 54].

Declarations

Conflict of interest There are no relevant financial or non-financial competing interests related to this work.

References

1. Ando, S., Kida, N., Oda, S.: Practice effects on reaction time for peripheral and central visual fields. Percept. Mot. Skills **95**(3), 747–752 (2002)
2. Frison, A.K., Forster, Y., Wintersberger, P., Geisel, V., Riener, A.: Where we come from and where we are going: a systematic review of human factors research in driving automation. Appl. Sci. (Switzerland) **10**(24), 1–36 (2020). https://doi.org/10.3390/app10248914
3. Götze, M., Bißbort, F., Petermann-Stock, I., & Bengler, K: A careful driver is one who looks in both directions when he passes a red light. Increased demands in urban traffic (2014).
4. Häuslschmid, R., Osterwald, S., Lang, M., Butz, A.: Augmenting the driver's view with peripheral information on a windshield display. International Conference on Intelligent User Interfaces. Proceedings IUI, 311–321. https://doi.org/10.1145/2678025.2701393 (2015)
5. Heymann, M. and Degani, A.: Classification and organization of information. In: Design of multimodal mobile interfaces, DE GRUYTER, 195–217 (2016).
6. Feierle, A., Beller, D., Bengler, K.: Head-up displays in urban partially automated driving: effects of using augmented reality. IEEE Intelligent Transportation Systems Conference (ITSC), 1877–1882 (2019)
7. Continental: User Experience Head-up Displays. http://continental-head-updisplay.com (2016). Accessed 20 March 2022
8. Pečečnik, K., Tomažič, S., Sodnik, J.: Design of head-up display interfaces for automated vehicles. Int. J. Human Comput. Stud. (2023). https://doi.org/10.1016/j.ijhcs.2023.103060
9. Langlois, S., Soualmi, B.: Augmented reality versus classical HUD to take over from automated driving: An aid to smooth reactions and to anticipate maneuvers. IEEE 19th International Conference on Intelligent Transportation Systems, 1571–1578 (2016)
10. Tretten, P., Gärling, A., Nilsson, R., Larsson, T.C.: An onroad study on head-up display preferred location and acceptance levels. Proc. Human Factors Ergon. Soc. **55**(1), 1914–1918 (2011)
11. Yoo, H., Tsimhoni, O., Watanabe, H., Green, P., Shah, R.: Display of HUD Warnings to Drivers: Determining an Optimal Location, (Technical Report UMTRI-99-5, ITS RCE report #939423), Ann Arbor. University of Michigan Transportation Research Institute, MI (1999)
12. Ma, X., Jia, M., Hong, Z., Kwok, A.PKi., Yan, M.: Does augmented-reality head-up display help? A preliminary study on driving performance through a VR-simulated eye movement analysis. IEEE Access **9**, 129951–129964 (2021). https://doi.org/10.1109/ACCESS.2021.3112240
13. Liu, Y.C., Wen, M.-H.: Comparison of head-up display (HUD) vs. head-down display (HDD): driving performance of commercial vehicle operators in taiwan. Int. J. Human Comput. Stud. **61**(5), 679–697 (2004). https://doi.org/10.1016/j.ijhcs.2004.06.002
14. Currano, R., Park, S.Y., Moore, D.J., Lyons, K., Sirkin, D.: Little road driving hud: Heads-up display complexity influences drivers' perceptions of automated vehicles. In: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, 1–15 (2021)
15. Gabbard, J. L., Fitch, G.M., Kim, H.: Driver queries using wheel-constrained finger pointing and 3-D head-up display visual feedback. Proceeding of the 5th International conference on automotive User interfaces and Interactive vehicular application, 52–62 (2014)
16. Fujimura, K., Xu, L., Tran, C., Bhandari, R., Ng-Thow-Hing, V.: Driver queries using wheel-constrained finger pointing and 3-D head-up display visual feedback. Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, 56–62 (2013)
17. Horrey, W.J., Wicken, C.D., Alexander, A.L.: The effects of head-up display clutter and in-vehicle display separation on concurrent driving performance. Proc. Human Factors Ergon. Soc. Annu. Meet. **47**(16), 1880–1884 (2003)
18. Riegler, A., Riener, A., Holzmann, C.: Augmented reality for future mobility: insights from a literature review and HCI workshop. I-Com **20**(3), 295–318 (2021). https://doi.org/10.1515/icom-2021-0029
19. Jakus, G., Dicke, C., Sodnik, J.: A user study of auditory, head-up and multi-modal displays in vehicles. Appl. Ergon. **46**, 184–192 (2015). https://doi.org/10.1016/j.apergo.2014.08.008
20. Pauzie, A.: Head up display in automotive: a new reality for the driver. International Conference of Design, User Experience and Usability, 505–516 (2015)
21. Lüke, S., Fochler, O., Schaller, T., Regensburger, T.: Stauassistenz und -automation, in Handbuch Fahrerassistenzsysteme, 3. Auflage, ed. by H.~Winner, S. Hakuli, F. Lotz, C. Singer (Springer Vieweg, Wiesbaden, 2015).

22. Miličić, N.: Sichere und ergonomische Nutzung von Head_up_Displays im Fahrzeug. Dissertation, TUMunchen (2010)
23. Raubitschek, C.: Prioritätenorientierte Implementierung einer Menüinteraktion im Head-Up Display für den Automobilbereich. Diplomarbeit, Lehrstuhl für Mensch-Maschine-Kommunikation, TUM, München (2008).
24. Park, J., Park, W.: A review on the interface design of automotive head-up displays for communicating safety-related information. Proc Hum Factors Ergon Soc Annu Meet **63**(1), 2016–2017 (2019). https://doi.org/10.1177/1071181319631099
25. Merenda, C., Smith, M., Gabbard, J., Burnett, G., Large, D.: Effects of real-world backgrounds on user interface color naming and matching in automotive AR HUDs. IEEE Workshop on Perceptual and Cognitive Issues in AR, 57–68. https://doi.org/10.1109/PERCAR.2016.7562419 (2016)
26. Smith, S., Fu, S.: The relationships between automobile head-up display presentation images and drivers' kansei. Displays **32**(2), 58–68 (2011). https://doi.org/10.1016/j.displa.2010.12.001
27. Brown, A.S., Birman, V., Miciuda, E.: Optimization suggestions for instrument-cluster information using displays. J. Soc. Inform. Display **19**(10), 665–670 (2011). https://doi.org/10.1889/JSID19.10.665
28. Alves, P. R. J. A., Goncalves, J., Rossetti, R. J. F., Oliveira, E. C., Olaverri-Monreal, C.: Forward collision warning systems using heads-up displays: Testing usability of two new metaphors. IEEE Intelligent Vehicles Symposium, 1–6. https://doi.org/10.1109/IVS.2013.6629438 (2013)
29. Beck, D., Jung, J., Park, J., Park, W.: A study on user experience of automotive HUD systems: contexts of information use and user-perceived design improvement points. Int. J. Hum.-Comput. Interact. **35**(20), 1936–1946 (2019). https://doi.org/10.1080/10447318.2019.1587857
30. Li, X., Schroeter, R., Rakotonirainy, A., Kuo, J., Lenné, M.G.: Effects of different non-driving-related-task display modes on drivers' eye-movement patterns during take-over in an automated vehicle. Transport. Res. F: Traffic Psychol. Behav. **70**, 135–148 (2020)
31. Helander, M., Landauer, T., Prabhu, P.: Handbook of Human-Computer Interaction. Elsevier (1997)
32. Campbell, F.W.: The depth of field of the human eye. Opt. Acta **4**, 157–164 (1957)
33. Velger, M.: Helmet-Mounted Displays and Sights. Artech House, Boston, London (1997)
34. Schomig, N., Wiedemann, K., Naujoks, F., Neukum, A., Leuchtenberg, B., Vohringer- Kuhnt, T.: An augmented reality display for conditionally automated driving. Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, 137–141 (2018)
35. Peli E.: Optometric and perceptual issues with head-mounted display (HMD). In: Mouroulis P, ed. Optical Design for Visual Instrumentation. McGraw-Hill, New York. pp. 205–276. (1999)
36. Singh, S. S., Pattnaik, S. S., Sardana, H. K., Bajpai, P. P. :Analysis of errors and distortions in stroke form of symbology for head-up displays. Paper presented at the Lecture Notes in Engineering and Computer Science 2196, 1302-1306 (2012)
37. McPhee, L.C., Scialfa, C.T., Dennis, W.M., Ho, G., Caird, J.K.: Age differences in visual search for traffic signs during a simulated conversation. Hum. Factors **46**(4), 674–685 (2004). https://doi.org/10.1518/hfes.46.4.674.56817
38. Edgar, G.K.: Accommodation, cognition, and virtual image displays: a review of the literature. Displays **28**(2), 45–59 (2007). https://doi.org/10.1016/j.displa.2007.04.009
39. Bach, M.: Manual of the Freiburg Vision Test 'FrACT', Version 3.9.8. http://www.michaelbach.de/fract/media/FrACT3_Manual.pdf. Accessed 10 March 2017
40. Peters, M., Ivanoff, J.: Performance asymmetries in computer mouse control of right-handers, and left-handers with left- and right-handed mouse experience. J. Mot. Behav. **31**(1), 86–94 (1999)
41. Maruyama, A., Takahashi, K., Rothwell, J.C.: Interaction between left dorsal premotor and right primary motor cortex during a left hand visual go/no-go reaction time. Brain Stimul.Stimul. **1**(3), 255 (2008). https://doi.org/10.1016/j.brs.2008.06.081
42. Colenbrander A. Consilium Ophthalmologicum Universale Visual Functions Committee. Visual acuity measurement standard. Italian Journal of Ophthalmology. **2**(1), 1–15 (1988)
43. USA Department of Defense: Human engineering design criteria for military systems, equipment and facilities (MIL-STD1472 F). Navy Publishing and Printing Office, Philadelphia, PA (1998)
44. Woodworth, R.S., Schlosberg, H.: Experimental Psychology. Henry Holt, New York (1954)
45. Pastor MA., Artieda J. (Eds.): Time, Internal Clocks, and Movement, Elsevier (1996).
46. Artieda, J., Pastor, M.A., Lacruz, F., Obeso, J.A.: Temporal discrimination is abnormal in Parkison disease. Brain **115**, 199–210 (1992)
47. Green, J.B., Reese, C.L., Pegues, J.J., Eliot, F.A.: Ability to distinguish two cutaneous stimuli separated by a brief time interval. Neurology **11**, 1006–1010 (1961). https://doi.org/10.1212/wnl.11.11.1006
48. Knott, V. C., Demmelmair, S., Bengler, K.: Distraction and driving behavior by presenting information on an "emissive projection display" compared to a head-up display. Proceedings of the 12th International Conference Engineering Psychology and Cognitive Ergonomics https://doi.org/10.1007/978- 3–319–20373–7_2 (2015)
49. Betancur, J.A., Suarez, D.: System and method for interacting with a mobile device using a head-up display. United States Trademark and Patent Office, Alexandria (2023)
50. Lif, P., Oskarsson, P.A., Lindahl, B., Hedström, J., Svensson, J.: Multimodal threat cueing in simulated combat vehicle with tactile information switching between threat and waypoint indication. In: Symposium on Human Interface, pp. 454–461. Springer (2011)
51. François, M., Osiurak, F., Fort, A., Crave, P., Navarro, J.: Automotive HMI design and participatory user involvement: review and. Ergonomics **60**, 541–552 (2016). https://doi.org/10.1080/00140139.2016.1188218
52. Betancur, J.A., Gómez, N., Castro, M., Suárez, D., Merienne, F.: User experience comparison among touchless, haptic and voice head-up displays interfaces in automobiles. Int. J. Interact. Des. Manuf. **12**, 1469–1479 (2018). https://doi.org/10.1007/s12008-018-0498-0
53. Betancur, J.A., Villa-Espinal, J., Osorio-Gómez, G., Cuellar, S., Suárez, D.: Research topics and implementation trends on automotive head-up display systems. Int. J. Interact. Des. Manuf. **12**, 199–214 (2018). https://doi.org/10.1007/s12008-016-0350-3
54. Ware, C.: Information visualization: perception of design. Morgan Kaufmann, San Francisco (2019)