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Design Strategies Compared: How eHMI Are Perceived in Relation to the Exterior Design of Automated Vehicles

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ABSTRACT

Communication between road users, especially between vulnerable road users and drivers, is an important part of road traffic. With the introduction of automated vehicles in road traffic, the possibility of non-verbal communication with the vehicle driver is no longer available. In the future, communication between road users and automated vehicles will take place via external HMI concepts (eHMI). In the context of this paper, an eye-tracking study was designed to investigate the influence of the degree of integration of eHMI concepts on the design perception of the test subjects. The evaluation of the test subjects with regard to various factors provides statements about the system trust and the perception of safety through eHMI, the appeal and recognisability of eHMIs as well as the interaction with the sensor clusters typical for automated vehicles.

Keywords: External HMI (eHMI), Exterior-design, Transportation design, Human-vehicle-interaction, Trust in automation

INTRODUCTION

Communication between road users, especially between vulnerable road users and drivers, is an important part of road traffic. Often, small nuances such as gestures, facial expressions or eye contact determine the subsequent behaviour of those involved. For example, eye contact with the driver helps pedestrians to make a decision about when to cross the road. With automated vehicles (AVs), the ability to communicate with the person in the driver's seat is limited, as they no longer necessarily control the vehicles behaviour. AVs detect their environment via a multitude of sensors. Towards the environment, however, a communication channel has been missing until the latest research about external human-machine interfaces (eHMI). For eHMIs, there are various concepts and studies on design, modality and positioning (Carmona et al., 2021). So far, there is a lack of experience on the integration of eHMIs into the exterior design of vehicles in terms of their perception by pedestrians and other road users. A large number of studies have already shown that vehicle exterior design has an influence on people's subjective perception and associated actions (cf. Mandel et al., 2015; Reichelt et al., 2020).

In this paper, this preconditioning will be investigated in relation to the degree of integration of eHMI in interaction with visible or invisible sensor clusters. For this purpose, different degrees of eHMI integration are applied to a concept car and investigated in an eye-tracking study with regard to their influence on the sensations of other road users. This results in findings for the design of safety-relevant eHMIs to strengthen the trust in AVs among the general population.

THEORETICAL BASICS

Automated vehicles have so far differed from conventional vehicles in their external appearance. Particularly noticeable are the sensors of AVs, which detect environmental influences and regulate the respective driving functions (Fischer et al., 2021). There is potential to optimally integrate these into the exterior design (Fischer et al., 2021). According to Fischer et al. (2021), sensors can be supplemented additively or integratively into the vehicle design. The same applies to eHMI. The external human-machine interface, which in the future will handle most of the communication between the AV and other road users, must be considered as part of the exterior, just like the sensors. While sensors have to fulfil certain positioning requirements with regard to the technical boundary conditions (Fischer et al., 2021), quick and clear recognisability is of great importance for the eHMI. The art of vehicle designers is to ensure this recognisability, for example via salient stimuli (Anderson et al., 2011), while at the same time maintaining a coherent and aesthetic exterior design. For eHMIs, there are already studies that deal with the modality, the positioning on the vehicle or the design of the interface. Eisma et al. (2020) found that positioning the eHMI in the grill, on the windscreen or on the roof offers the best performance in terms of recognisability. The location of the eHMI in these positions does not have a significantly different impact on the perception of the respondents, but a positioning on the grill and windscreen is more in line with the usual visual behaviour of pedestrians and therefore useful (Guo et al., 2022). Eisma et al. (2020) also found in the study that an eHMI is also helpful on the side of the vehicle when the front is not visible, for example, when turning. This is supported by the research of Troel-Madec et al. (2019), where the vehicle fronts of a queue of cars were partially obscured and thus not visible to passers-by.

There are various studies on the modality of eHMI (cf. Beggiato et al., 2017; Burns et al., 2019; Carmona et al., 2021; Dey et al., 2021; Lim and Kim, 2022). Bazilinskyy et al. (2019) concluded that the text form with direct address of passers-by is best suited for quick information transfer for most people.

As it turns out, there are already various studies and knowledge of eHMI design, related to modality, positioning as well as the design and recognisability of eHMI itself. What has not been considered much so far, is a methodical and design-strategic investigation of the integration of eHMIs into the exterior design. In this paper, the integration possibilities of eHMI will be investigated on the basis of the exterior design of an example vehicle. The example used is a concept car from the federally funded research project RUMBA, see Figure 1.

Figure 1: RUMBA concept car.

The vehicle was designed by the design studio studiokurbos in Stuttgart as part of the project. It is an IC body with a rising front (I) and a cubic rear end (C) (Holder, 2016). This example vehicle is used to show the different possibilities of integrating eHMI into the exterior design of vehicles. The type of integration is divided into additive, integrative and integral design (cf. Ferraris et al., 2017). In additive design, the eHMI is added to the actual vehicle design by means of a roof bar. The shape of the vehicle changes visibly. This is in contrast to integral design. Here, the eHMI is integrated into the existing vehicle design as far as possible. For this example vehicle, this is done via central displays in the black areas of the design. The vehicle design is hardly changed, the eHMI appears more like an additional graphic on the existing design, which is covered with colour. The third option of integrating the eHMI into the vehicle's exterior is a kind of compromise between the two previously mentioned options. With integrative design, the eHMI is not fully integrated into the existing shape as in integral design, but the shape is not changed as much as in additive design. In this case, the eHMI is visualised via a quasi circumferential display below the vehicle roof.

METHODS

To find out what influence the integration of eHMI into the vehicle exterior has on the design perception of automated vehicles, a two-part eyetracking study was developed. One part dealt with the integration of sensor clusters into the exterior design and the other part with the integration of eHMI into the exterior design and possible interactions with the sensor clusters. In this paper, only the part on eHMI and the interactions with sensor technology is presented. The test persons were shown renderings in 3/4 front and 3/4 rear perspective of a concept car on the screen, which represent different degrees of integration of eHMI. In one half of the stimulus patterns, the vehicle exterior contained only the eHMI, the other half showed the exterior with eHMI and sensors. The stimulus patterns were shown to the participants for 20 seconds each in order to obtain meaningful and comparable results with a real traffic situation. During this time, the subjects' eye movements were recorded with a Tobii eye-tracking system. After each shown stimulus pattern, the subjects rated each of the stimulus patterns by questionnaire regarding their subjective impression in the context of a use case (Road Crossing Scenario, following Joisten et al. (2021)). The order of the different parts of the study as well as the order of the stimulus patterns within a part of the study were randomised.

In the study, the test persons were shown six stimulus patterns for evaluation. The stimulus patterns are divided into three pairs with specific eHMI configurations, each without and with visible sensors. The eHMI configurations are based on the “additive, integrative and integral” design strategies described above for integrating eHMI into the vehicle exterior.

The positioning of the eHMI depends on the level of integration and is chosen based on the findings of Eisma et al. (2020). Text was chosen as the modality, according to Bazilinskyy et al. (2019). This is shown on the front, side and rear of the vehicle. The colour of the text is based on the colour of the vehicle’s paint. The stimulus pattern RMH1 shows the vehicle with additive eHMI in the form of an attached display on the roof, above the windscreen. At the sides and rear, the eHMI also runs at the height of the roof edge. Sensors are not visible here. The stimulus pattern RMH2 shows the same configuration as RMH1, but is additionally equipped with sensors on the exterior. These are clearly highlighted in contrasting colour (orange). The stimulus patterns RMH3 and RMH4 show the integrative eHMI. Here, the text display is integrated into the windscreen below the edge of the roof. At the sides and rear, the text again runs below the edge of the roof. RMH4 shows the sensors in contrast colour in addition to the configuration of RMH3. The stimulus patterns RMH5 and RMH6 show the integral design of the eHMI. Here, the text runs in the black area at the front of the vehicle, below the windscreen. The display is thus completely integrated into the vehicle’s exterior design. At the side and rear of the vehicle, the display is also integrated into a black area at the level of the belt hight. RMH 6 shows the sensors in contrasting colour in addition to the configuration of RMH5. Figure 2 shows an overview of the six described stimulus patterns.

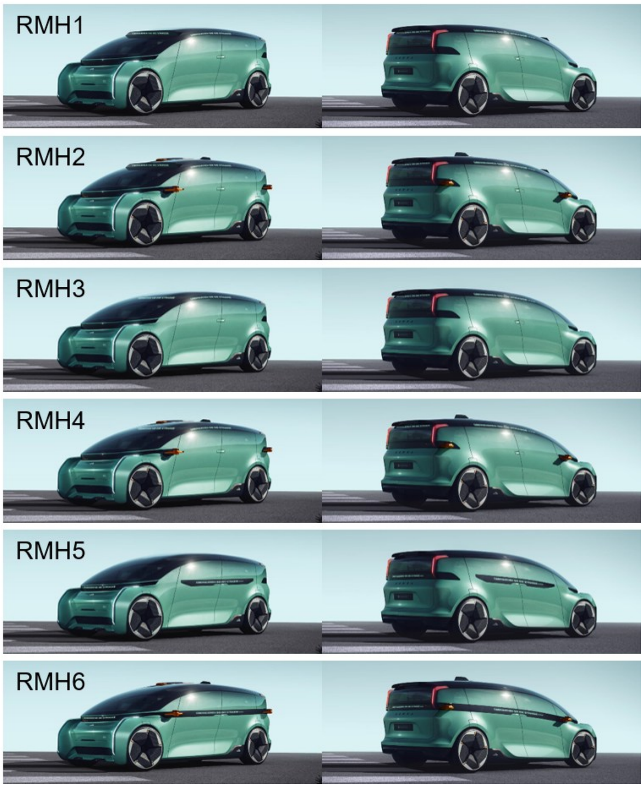

Figure 2: Stimulus patterns of the concept car with eHMI presented to test persons.

The questionnaire of this part of the study consisted of a total of 15 items that remained the same for all stimulus patterns. The items were rated using a six-point Likert scale (1 = "strongly disagree" to 6 = "strongly agree"). The aim of the survey was to gain insights into the influence of the type of integration of eHMI in the vehicle exterior on the four sub-areas of recognisability, system trust, safety perception and appeal. In addition, a possible interdependence through the visibility of sensors was to be investigated. For the recognisability of the eHMI, adapted items according to Bazilinskyy et al. (2019) as well as self-developed items were used. System trust was assessed using relevant, adapted items from the Trust-in-Automation questionnaire according to Körber (2018) and Ekman (2020). Items according to Arndt (2010), Salonen (2018) and Bazilinskyy et al. (2019) were used to assess the perception of safety. The appeal was evaluated with items according to Holder (2016) as well as further self-developed items.

RESULTS AND DISCUSSION

In the following, the results of the eye tracking study on the integration of eHMI into the exterior design of automated vehicles are presented. A total of 36 subjects took part in the study. The sample consisted of 15 female and 21 male participants aged between 18 and 65 years (see Figure 3). The majority of the test persons (n = 32) were between 18 and 30 years of age.

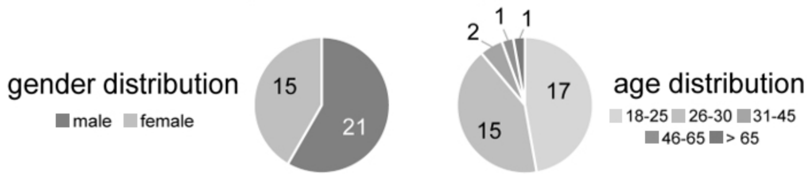

Figure 3: Gender and age distribution of participant collective.

The statistical evaluation of the questionnaire of the main study is shown in the following boxplot diagrams. The boxplot diagrams are clustered according to the items in the above-mentioned categories of recognisability, system trust, perception of safety and appeal. For all questions, an ANOVA with repeated measures and Huynh-Feldt correction with subsequent Bonferroni-corrected comparisons in pairs of the significant stimulus patterns were carried out as part of the statistical evaluation. The statistical results can be found in Table 1–4.

Figure 4 shows a positive trend in the recognisability of the eHMI. All design strategies seem to be recognisable well. Especially the additive and the integral design perform well. The integrative design is significantly less recognisable. A significant influence of the visibility of sensors is not seen, except that RMH5 distracts less from the message shown than RMH4.

Table 1. Statistical evaluation of the questions on recognisability.

Recognisability quest. 1	Recognisability quest. 2	Recognisability quest. 3	Recognisability quest. 4
Mauchly-W(2) = .440 p = .019 HF = .874 F(21.968, 184.532) = 4.167 p = .002 partial η^2 = .106	Mauchly-W(2) = .565 p = .170 HF = .970 F(18.278, 192.389) = 3.325 p = .007 partial η^2 = .087	Mauchly-W(2) = .312 p < .001 HF = .805 F(20.556, 185.778) = 3.873 p = .005 partial η^2 = .100	Mauchly-W(2) = .702 p = .632 HF = 1.000 F(19.426, 228.907) = 5.000 p = .013 partial η^2 = .078

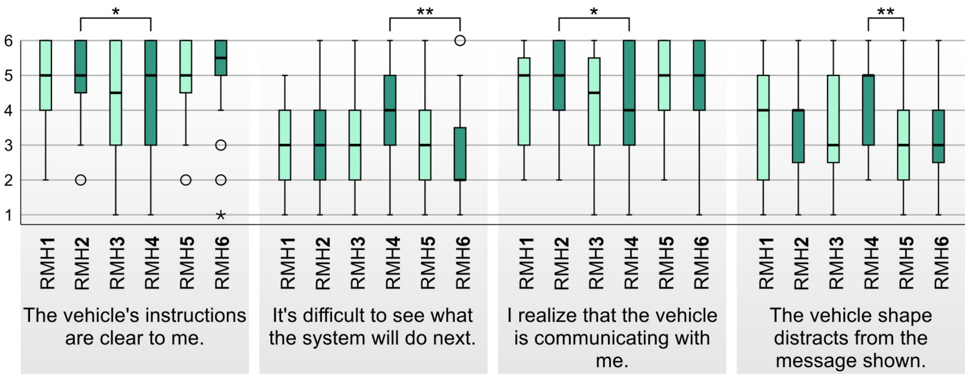

Figure 4: Boxplots for recognisability.

Figure 5 shows the results of the questions on system trust. Here, too, a tendency in a positive direction can be seen for all stimulus patterns. The stimulus pattern RMH3 with integrative design without sensors was rated significantly worse in all three questions than the integral design with sensors RMH6. In general, the integral design was also rated better than the integrative design.

Table 2. Statistical evaluation of the questions on system trust.

System trust question 1	System trust question 2	System trust question 3	
Mauchly-W(2) = .445 p = .021 HF = .854 F(15.597, 105.569) = 5.171 p <.001 partial $\eta 2$ = .129	Mauchly-W(2) = .675 p = .527 HF = 1.000 F(11.037, 98.630) = 3.917 p = .002 partial $\eta 2$ = .101	Mauchly-W(2) = .475 p = .039 HF = .924 F(8.097, 97.736) = 2.900 p = .018 partial $\eta 2$ = .077	Mauchly-W(2) = .366 p = .003 HF = .765 F(20.412, 116.088) = 6.154 p < .001 partial $\eta 2$ = .150

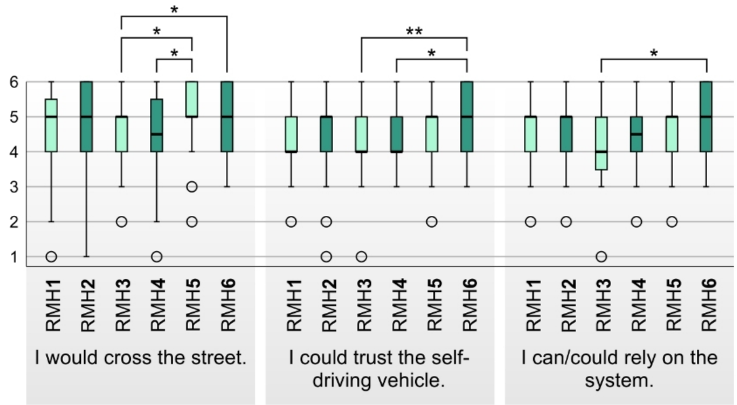

Figure 5: Boxplots for system trust.

The ratings of the questions on safety perception are shown in Figure 6. Especially the diagram for the first question shows that the interaction of eHMI and the visibility of sensors has significant effects on the perception of safety standards. Stimulus patterns with sensors are rated significantly better than stimulus patterns without sensors. With regard to the perception of safety, the integrative design without sensors (RMH3) was perceived significantly worse than the additive design variants and the integral design with sensors (RMH6).

Table 3. Statistical evaluation of the questions on the perception of safety.

Safety question 1	Safety question 2	Safety question 3	Safety question 4
Mauchly-W(2) = .366 p = .003 HF = .765 F(20.412, 116.088) = 6.154 p < .001 partial η^2 = .150	Mauchly-W(2) = .623 p = .337 HF = .984 F(11.301, 89.866) = 4.401 p < .001 partial η^2 = .112	Mauchly-W(2) = .595 p = .248 HF = .944 F(6.856, 78.977) = 3.039 p = .014 partial η^2 = .080	Mauchly-W(2) = .580 p = .207 HF = .928 F(5.815, 90.852) = 2.240 p = .057 partial η^2 = .060

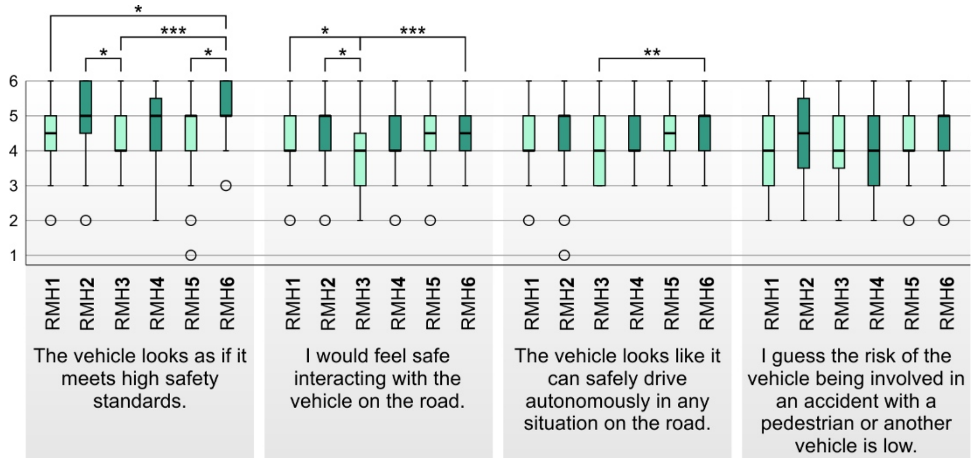

Figure 6: Boxplots for safety.

As Figure 7 shows, there are clear significant differences between the design variants with regard to appeal. In terms of subjective appeal, all variants with sensors were rated significantly worse than the variants without sensors. The variants with sensors also scored significantly worse in the second question. The sensors in the RMH2, 4 and 6 variants tended to be perceived as disturbing in terms of design effect, in some cases even significantly disturbing.

Table 4. Statistical evaluation of the questions on the appeal.

Appeal question 1	Appeal question 2	Appeal question 3	Appeal question 4
Mauchly-W(2) = .608 p = .287 HF = .916 F(30.856, 166.644) = 6.481 p < .001 partial η^2 = .156	Mauchly-W(2) = .560 p = .160 HF = .897 F(58.537, 126.463) = 16.201 p < .001 partial η^2 = .316	Mauchly-W(2) = .430 p = .015 HF = .834 F(24.222, 171.778) = 4.935 p < .001 partial η^2 = .124	Mauchly-W(2) = .689 p = .583 HF = .866 F(25.690, 135.810) = 6.621 p < .001 partial η^2 = .159

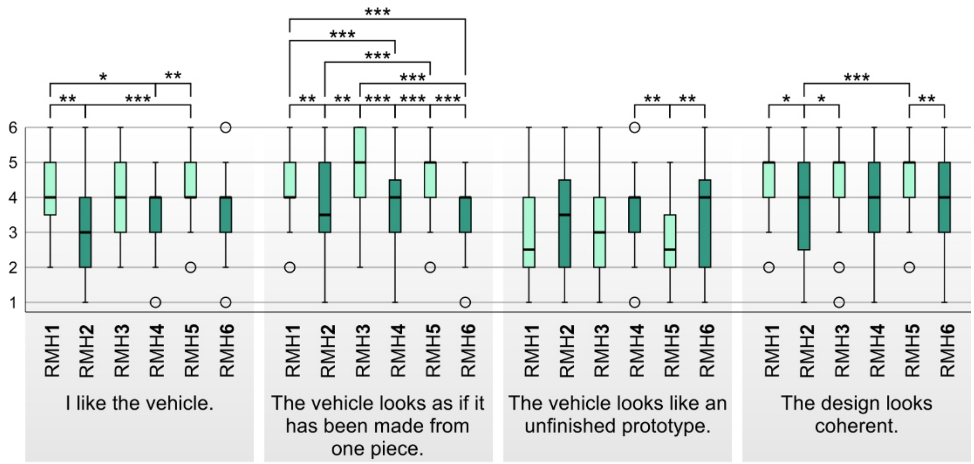

Figure 7: Boxplots for appeal.

Table 5 shows the significances between the stimulus patterns evaluated in the evaluation of the individual questions.

Figure 8 displays the results of the eyetracking study. The heatmaps shown describe the subjects' fixations on the respective stimulus patterns. Due to technical problems, the evaluation of the eye-tracking data unfortunately has a high error rate. Out of a total of 36 subjects, only 19 data sets could be used to create the heat maps. The other 17 data sets were not considered for the graphical evaluation of the eye-tracking. The evaluation of the heat maps shows across all stimulus patterns that the front of the vehicle was predominantly observed. The stimulus patterns without sensors (RMH1, RMH3, RMH5) clearly show a fixation of the eHMI at the front of the vehicle as well

Table 5. Significances between the stimulus patterns.

Recognisability quest. 1	Recognisability quest. 2	Recognisability quest. 3	Recognisability quest. 4
RMH 2–4: p = .031	RMH 4–6: p = .007	RMH 2–4: p = .023	RMH 4–5: p = .009
System trust question 1	**System trust question 2**	**System trust question 3**	
RMH 3–5: p = .012	RMH 3–6: p = .006	RMH 3–6: p = .031	
RMH 3–6: p = .041	RMH 4–6: p = .028		
RMH 4–5: p = .016			
Safety question 1	**Safety question 2**	**Safety question 3**	**Safety question 4**
RMH 1–6: p = .021	RMH 1–3: p = .024	RMH 3–6: p = .004	-
RMH 2–3: p = .025	RMH 2–3: p = .039		
RMH 3–6: p <.001	RMH 3–6: p = .001		
RMH 5–6: p = .041			
Appeal question 1	**Appeal question 2**	**Appeal question 3**	**Appeal question 4**
RMH 1–2: p = .003	RMH 1–2: p = .003	RMH 4–5: p = .006	RMH 1–2: p = .016
RMH 1–4: p = .022	RMH 1–4: p <.001	RMH 5–6: p = .007	RMH 2–3: p = .034
RMH 2–5: p <.001	RMH 1–6: p <.001		RMH 2–5: p = .001
RMH 4–5: p = .006	RMH 2–3: p = .002		RMH 5–6: p = .004
	RMH 2–5: p <.001		
	RMH 3–4: p = .001		
	RMH 3–6: p <.001		
	RMH 4–5: p <.001		
	RMH 5–6: p <.001		

as at the side and rear. In the stimulus patterns with sensors (RMH2, RMH4, RMH6) it is clear that the fixations of the eHMIs decrease to a small extent and that some of the strongly focused areas shift towards the sensors at the corners of the vehicle. In the comparison of the different design strategies, the integral design of the eHMI (RMH5 and RMH6) is fixed most often by the subjects. A closer look shows that most of the gaze concentrations are directly on the eHMI. The additive design (RMH1 and RMH2) also shows clearly focussed areas, but less specifically than the integral design. The integrative design (RMH3 and RMH4) has comparatively fewer gaze concentrations in the area of the eHMI.

The predominant consideration of the front side can certainly be explained by the use case of the road crossing scenario. The subjects were asked to imagine a zebra crossing where they would like to cross the road while an automated vehicle is approaching. Normally, the subjects would see the front of the vehicle at the crossing. The shift in gaze concentrations in the stimulus patterns RMH2, RMH4 and RMH6 compared to the stimulus patterns RMH1, RMH3 and RMH5 suggest that the sensors are the cause of the change in viewing the stimulus patterns. The tendency from the boxplots of the item "The vehicle shape distracts from the message shown" is supported by this. Even though the subjects did not explicitly state in the questionnaire that they looked less at the eHMI due to the presence of the sensors, the heatmaps show, that they did so subconsciously to a large extent.

With regard to the design strategies, it becomes clear that the additive design and the integral design perform similarly well. When looking at the

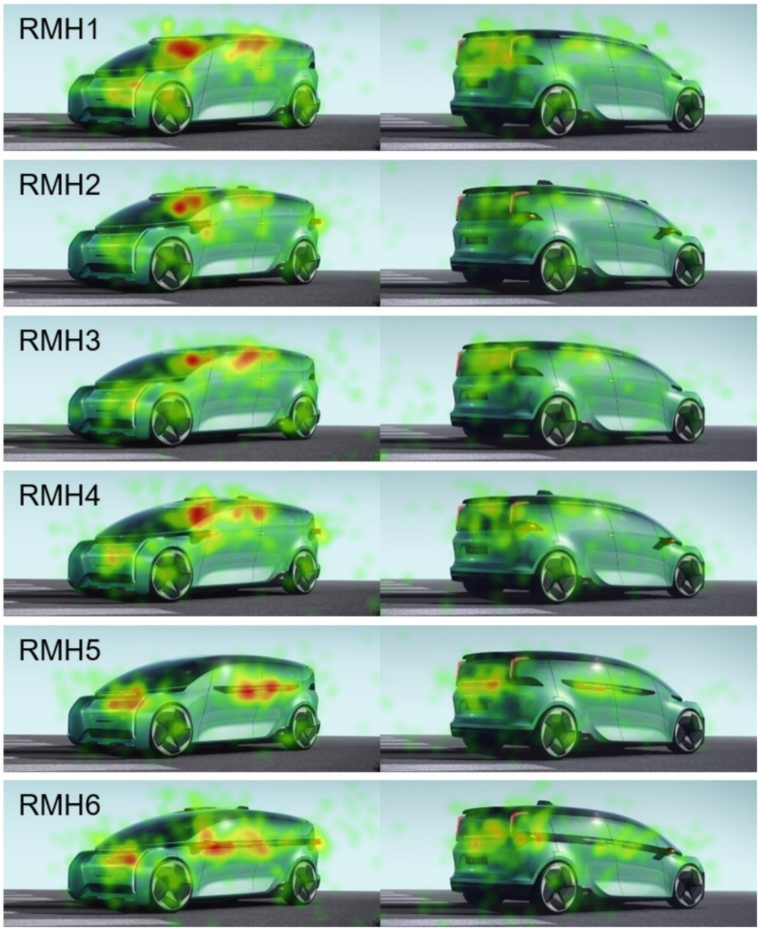

Figure 8: Results of the eyetracking analysis shown via heatmaps.

heat maps, it shows that the integrative solution performs the worst. If the results are compared with the boxplots for recognisability, it becomes clear that the integral design is best received by the test persons.

From the study results it can be concluded that an interaction between eHMI and sensors cannot be ruled out. The sensors distract the viewer's gaze at least partially from the eHMI. For the exterior design, this means that the sensors should be designed to be as invisible as possible and that the eHMI should be a salient stimulus for quick recognition. Nevertheless, the eHMI can easily be fully or integrally integrated into the vehicle design. Compared to the additive and integrative design, the integral design also has advantages in terms of appeal and thus also contributes to the aesthetics and presumably also to the acceptance of future vehicles.

With regard to the significance of the results, the study setting must be viewed critically in terms of immersion. The static stimulus patterns shown represent an initial tendency of the test persons with regard to the questions. In order to obtain more detailed results, a dynamic presentation of the stimulus patterns, ideally with real vehicles at a real crossing, would be helpful. In addition, further scenarios and different vehicle concepts should be tested in order to substantiate the validity of the eHMI information.

CONCLUSION AND OUTLOOK

The research has shown that the type and degree of integration of eHMI into the vehicle exterior design is of relevant importance for design perception, evaluation and thus design. The degree of integration has an impact on perception factors such as recognisability or appeal of AVs. To replace the subtle but efficient communication between driver and pedestrian in the context of a future vehicle exterior design, it is advantageous if the eHMI represents a salient stimulus and is unambiguously interpreted. In order to guarantee an unambiguous interpretation of the information of the eHMI by the persons concerned, further possibilities for the creation of target-oriented external human-machine communication should be investigated. Furthermore, it should be investigated whether vehicles with a personalising exterior design and a human-interacting eHMI (cf. Jaguar Eye-Pods, VW Cedric) show more positive effects on communication and recognisability than conventional, machine-like eHMI. This would come close to merging classic vehicle design with robot design, i.e. transferring human characteristics to machines.

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