Digital Transformation in Automotive: Color Design of Cockpit Alerts for Effective and User-Friendly Driver Communication

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Abstract

The effectiveness of human-machine interfaces (HMI) in driving automation systems partially depends on how alerts and requests are delivered to the driver without unnecessarily distracting them from the driving task. Depending on the required user reaction time, alerts should be displayed differently - either capture attention immediately for a short duration or remain visible more subtly over time. Our study focuses on the use of color as a means of enhancing alert visibility and attention capture. Based on a user-centered experiment, we developed a ranking of color combinations for both day and night interface modes. Few existing studies address the adaptation of color to interface mode, and when they do, they primarily focus on contrast rather than differentiating alert types by importance. Our approach introduces an additional criterion - the criticality of the alert - that is a key factor in tailoring the visual design of warning signals.

Keywords: Automotive Visual Alerts, Color Design, Digital Transformation

1. Introduction

In the digital transformation era, the transportation sector is rapidly evolving to improve safety, comfort, and efficiency. Developing vehicles with various autonomy levels - designed to integrate with smart city infrastructure as defined by SAE [12] is a key aspect of this shift. However, ambitious timelines for highly autonomous vehicles remain unmet due to the complexity of the process, including data heterogeneity, vehicle-to-infrastructure communication, advanced algorithms, and challenges in AI, computer vision, regulations, standardization, and safety.

Modern vehicles are equipped with advanced multimedia systems, touchscreens, and adaptive visual alerts. At the same time, users must navigate a wide variety of interface designs and an increasing complexity of conveyed information. This highlights the need to better align visual communication with human perceptual capabilities and real-world driving conditions. However, there remains a research gap in empirically understanding how such perceptual and cognitive factors - especially those related to color perception - influence the rapid and accurate recognition of dashboard messages under varying lighting conditions. Human-centered design frameworks like Kansei Engineering emphasize the integration of cognitive and emotional user responses, yet their application in automotive visual interface design - particularly under real-world lighting variability - remains underexplored [9].

This study aims to fill this gap by evaluating how the visual design of automotive cockpits -particularly the use of color-coded alerts - affects the effectiveness and intuitiveness of driver communication. Specifically, we investigate how various visual features of alerts influence their noticeability and the user's subjective perception of usefulness. The analysis covers both perceptual aspects (e.g., attention capture, visibility under different conditions) and functional ones (e.g., matching color schemes to the urgency level of the message).

The main scientific contributions of the article include: (i) a critical analysis of the impact of user interfaces in vehicles on driver safety; (ii) an empirical investigation into color selection in automotive interfaces depending on display mode (day/night); (iii) the development of usability scenarios for in-vehicle interfaces related to the color design of various driver alerts and informational messages. The structure of the paper is as follows: Section 2 reviews the related work, and Section 3 outlines the conceptual framework. Section 4 details the experiment, results, and analysis. Finally, Sections 6 and 7 discuss the findings and outline future directions.

2. Literature review

In the context of in-vehicle interface design, standards such as ISO 15008:2017 [3] and those developed by CEN and CENELEC [1] play a crucial role in shaping ergonomic and safety-related aspects of cockpit design. ISO 15008:2017 sets international requirements for the visual ergonomics of information and control systems in vehicles, while CEN and CENELEC provide European road safety standards that, although not directly focused on interface aesthetics, influence cockpit design through specific technical requirements.

With the increasing integration of digital technologies into vehicles, user experience has become a central research focus. Richardson et al. [11] examine how modern interfaces, such as touchscreens and multimedia systems, affect driver interaction, usability, and performance. Their study highlights the importance of accounting for cognitive load and user accessibility when designing these systems, as they are vital to effective human-machine interaction. In the domain of vehicle automation, extensive research has been conducted on warning systems and their human-machine interfaces (HMIs), exploring different design modalities and specifications [10]. Based on established human interface ergonomics principles and standards (e.g., SAE, ISO), researchers have begun to propose guidelines for implementing effective automated vehicle interfaces. However, these guidelines are often fragmented and hard to apply in practice. Their implementation is limited by generality and technical constraints, such as processing limits, varying software architectures, and inconsistent user experience across systems. Moreover, rapid technological development often outpaces the revision cycle of standards, making timely adaptation even more difficult.

In 2024, a team from the University of Massachusetts-Amherst [14] conducted a literature review on human-machine interfaces (HMI) in driving automation. Despite extensive research on alert design, the study found limited practical application, which is critical amid the automotive industry's digital transformation. The review compiled existing HMI guidelines for automated driving, resulting in general design recommendations. However, these remain broad and lack specific guidance, highlighting the need for further research. **Kansei Engineering**, originally developed in Japan, integrates emotional and perceptual user responses in product design [9], yet its application in automotive HMI - particularly under dynamic lighting conditions - remains rare. The use of **multimodal information** transmission, combining auditory, visual, and tactile cues, is recommended to improve comprehension and accessibility. Visual displays should continuously show **system status** and key data to support situational awareness. **Intuitive icons**, preferred over text, enable quicker responses in critical moments and should follow industry standards for clarity. **The color scheme** also matters: red for emergencies, green for normal operation, and yellow for cautionary alerts.

HMI systems should clearly indicate the source of potential threats, allowing drivers to quickly assess the situation. **Feedback mechanisms** should explain control takeovers or emergency activations to improve driver readiness. Alerts should escalate in intensity based on urgency, using **multi-stage systems** that start with subtle visual cues and progress to auditory signals if needed, balancing effectiveness with minimal distraction.

This study builds on our previous research using eye-tracking to analyze color combinations that attract user attention both subjectively and objectively. We focus on evaluating color pairs for user-friendliness and attention-capturing using a forced-choice method. Interestingly, the most friendly and readable combinations often fell below WCAG contrast standards [5], scoring under 5.6:1 [6, 7, 8]. Based on these findings, we propose design guidelines for automotive visual alerts - both those meant to quickly capture attention briefly and those intended for longer, more pleasant user exposure.

3. Conceptual Framework

The research procedure is illustrated in Figure 1 and constitutes a systematic representation of the sequential stages of the experiment, leading to the development of final recommendations for the design of color-coded alerts in automotive user interfaces. The procedure was divided into five key steps, each of which played a crucial role in obtaining reliable and practically applicable results.

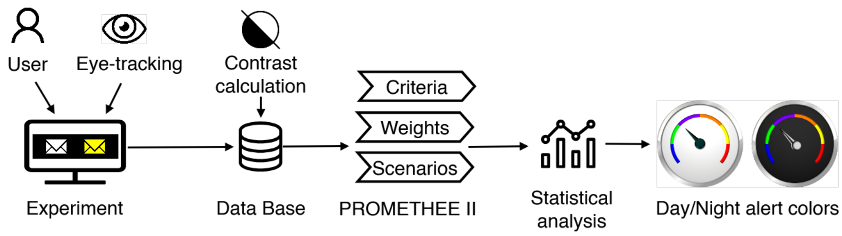

Fig. 1. The conceptual framework of our approach.

Step 1: Perceptual Experiment. The first stage involved a user experiment (see Section 4) **Step 2: Color Contrast Calculation**. For all pairs of colors used in the experiment, contrast values were calculated following the Web Content Accessibility Guidelines (WCAG). This enabled the development of a database that serves as a starting point for further analysis of colors in the context of cockpit interface design.
Step 3: Multicriteria Decision Analysis (MCDA) – PROMETHEE II Method. The collected data were subsequently analyzed using the PROMETHEE II multicriteria decision-making technique. This analysis enabled the ranking of color pairs based on two evaluation criteria: Friendly and Visible, and Rapid Attention Capture. The detailed specification of the scenarios and assigned weights is presented in the section Multicriteria Strategy and Scenario Specification.
Step 4: Statistical Analysis The next phase involved statistical data analysis, described in detail in the Statistical Analysis section.
Step 5: Development of the Recommended Color Ranking. The outcome of the analysis was the generation of a ranked list of recommended color pairs, dedicated to two user interface modes: day mode (light theme) and night mode (dark theme).

4. Experimental Study

Stimulus Characteristics and Experimental Conditions. To identify color pairs that are either intrusive or both attention-capturing and visually pleasant, 72 images were created. Each had a fixed background (black, gray, green, blue, violet, red, orange, yellow, or white) and a pictogram in a contrasting color. Images used a 1:2 aspect ratio and covered 40% of the screen.
Observers. The experiment was conducted with 35 observers aged 20–68, all with normal or corrected-to-normal vision. Each participant repeated the procedure three times, with sessions

held on different days to reduce learning effects.

Display conditions. The images were displayed on a 50% gray background, recommended by the International Color Consortium (www.color.org) for color comparison. The same background was used for the intervals between displayed pairs of images. The mouse cursor was reset after each trial. The experiment used a calibrated EIZO ColorEdge CG220 display and a Tobii Pro X3 (120 Hz) eye tracker, with a 60 cm viewing distance per Tobii guidelines [13]. Lighting was kept constant using 5000 K lamps (D50 standard), and ambient light was monitored with a Sekonic L-478DR meter. The color observation angle was 2^o.

Experimental procedure. Our methodology relied on perceptual experiments using a forced-choice pairwise comparison approach. Observers were presented with pairs of stimuli sharing the same background color but differing in pictogram color, and asked to choose the combination they found more attention-grabbing and visually pleasant. Prior to the test, participants read written instructions and completed a training session, following ITU-R [4]. To ensure engagement, three randomly selected trials were shown at the start and excluded from analysis. Stimuli were randomized per session, and consecutive trials with the same background color were avoided to reduce bias.

The experiment used eye-tracking to measure which color combination attracted attention first, complementing subjective preference data with objective metrics. Stimulus pairs were shown sequentially, separated by a neutral gray screen with a central fixation point to reset gaze and reduce carry-over effects. Stimuli appeared peripherally to avoid central fixation bias, ensuring attention was driven by the stimulus. Each session began with eye-tracker calibration before the main task.

5. Analysis

The analytical procedure comprised two principal stages: a multi-criteria decision-making approach and statistical analysis.

5.1. Multicriteria Strategy and Scenario Specification

In the analysis, we evaluated how color pairs attract attention using three criteria: subjective user ratings, objective eye-tracking data (first fixation), and color contrast. The PROMETHEE II method was employed to rank alternatives, supported by GAIA visualization for interpreting decision structures via principal component analysis (PCA). The decision vector π reflects the direction aligned with user preferences based on the applied weights.

Two decision-making scenarios were defined for both day and night contexts, differing in the distribution of criterion importance, where S (Subjective), O (Objective), and C (Contrast):

S1 (Day/Night) Friendly and Visible: S (70%), O (0%), C (30%)

S2 (Day/Night) Rapid Attention Capture: S (0%), O (70%), C (30%)

For each scenario and context (day/night) in Figure 2 A-D, a GAIA plot was generated. The vectors corresponding to the criteria indicate preference directions, while the green arrow (π) represents the synthetic decision vector. Analyzing the position of alternatives relative to the π vector makes it possible to identify the pairs of colors most aligned with the decision-maker's preferences. Alternatives closest to the π vector are considered the most preferred.

5.2. Scenario 1 (S1) and Scenario 2 (S2): Day and Night

The following analysis compares the effectiveness of color combinations under different lighting conditions and design intents, based on preference flows calculated using the PROMETHEE II method:

S1 (Day): According to PROMETHEE II (Table 1), the top-ranked color pairs were YellowBlack ($\phi = 0.3972$) and WhiteBlack ($\phi = 0.3755$), both with high positive flow (ϕ^+) and

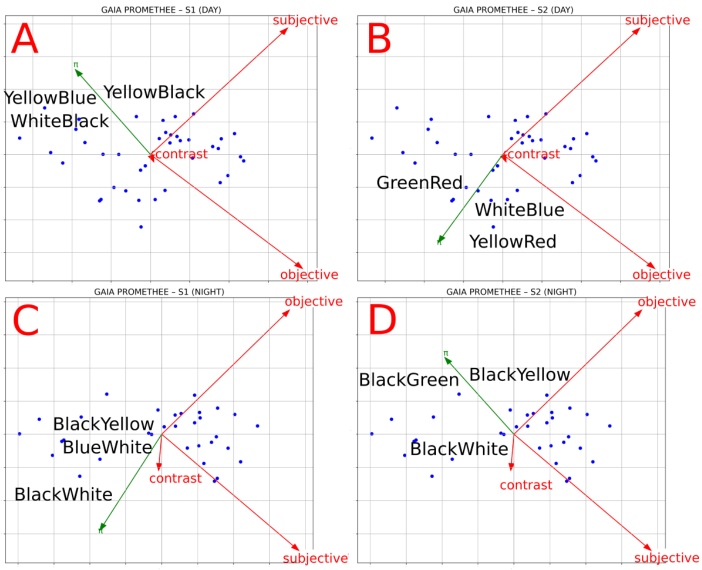

Fig. 2. GAIA for all scenarios: (A) S1 Day – Friendly and Visible, (B) S2 Day – Rapid Attention Capture, (C) S1 Night – Friendly and Visible, (D) S2 Night – Rapid Attention Capture.

Table 1. Ranking of pairs of colors based on PROMETHEE II net flow (ϕ) values in two decision scenarios (*Friendly and Visible* vs. *Rapid Attention Capture*) in two variants (*Day* and *Night*).

Friendly and Visible

	Day				Night			
rank	**back_pict**	ϕ^+	ϕ^-	ϕ	**back_pict**	ϕ^+	ϕ^-	ϕ
1	**YellowBlack**	0.4035	0.0063	0.3972	**BlackWhite**	0.4153	0.0152	0.4001
2	**WhiteBlack**	0.3895	0.0141	0.3755	**BlueWhite**	0.3495	0.0137	0.3358
3	**YellowBlue**	0.2966	0.0126	0.2841	**BlackYellow**	0.3572	0.0296	0.3276
4	**GreenBlack**	0.2987	0.0219	0.2769	**VioletWhite**	0.3196	0.0202	0.2994
5	**WhiteBlue**	0.2761	0.0137	0.2624	**BlueYellow**	0.3068	0.0183	0.2885

Rapid Attention Capture

	Day				Night			
rank	**back_pict**	ϕ^+	ϕ^-	ϕ	**back_pict**	ϕ^+	ϕ^-	ϕ
1	**WhiteBlue**	0.3363	0.0107	0.3255	**BlackGreen**	0.3691	0.0077	0.3614
2	**YellowRed**	0.2809	0.0253	0.2556	**BlackWhite**	0.3469	0.0277	0.3193
3	**GreenRed**	0.2734	0.0293	0.2442	**BlueYellow**	0.3335	0.0146	0.3191
4	**GrayYellow**	0.2521	0.0327	0.2193	**VioletGreen**	0.2782	0.0284	0.2498
5	**GreenBlue**	0.2158	0.0261	0.1898	**BlackYellow**	0.2851	0.0682	0.2169

minimal negative flow (ϕ^-). This suggests excellent visibility and user-friendly perception in daylight. Other options like YellowBlue and GreenBlack scored moderately.

S1 (Night): BlackWhite ($\phi = 0.4001$) ranked highest, followed by BlueWhite and BlackYellow, indicating strong suitability for low-light conditions. Slightly higher ϕ^- values point to more varied user preferences at night.

S2 (Day): WhiteBlue led the ranking ($\phi = 0.3255$), with YellowRed and GreenRed also scoring high ϕ^+ values, though with increased ϕ^-, indicating mixed responses-effective but potentially polarizing.

S2 (Night): BlackGreen ($\phi = 0.3614$) showed the best performance with low ϕ^-, followed by BlackWhite and BlueYellow. BlackYellow, with a higher ϕ^-, ranked lowest, possibly due to being perceived as overly intrusive in dark conditions.

5.3. Statistical Analysis

To compare color groups, the data were first standardized and then divided into four equal-width bins based on ranking scores: $< 0; 0.25)$, $< 0.25; 0.5)$, $< 0.5; 0.75)$, and $< 0.75; 1 >$, separately for subjective and objective results (see Table 2). The $< 0.75; 1 >$ range includes the most user-friendly and attention-grabbing combinations. Only 4% of color pairs fall into the $< 0; 0.25)$ bin. The middle two bins show even distribution, while most recommended pairs are found in the top bin.

Table 2. Subjective (top) and objective (bottom) data divided into four ranges. The first range shows the lowest scores, the fourth the highest.

Pictogram color - subjective ranking

Background color	*1st e-w bin <0;0.25)*	*2nd e-w bin <0.25;0.5)*	*3rd e-w bin <0.5;0.75)*	*4th e-w bin <0.75;1>*
black		gray	violet, blue, orange	red, green, yellow, white
blue	violet	gray	orange, red, black	green, yellow, white
gray		violet, blue, orange	red, black	green, white, yellow
green		yellow, orange	gray	red, white, violet, blue, black
orange		red, gray	violet, green	yellow, blue, white, black
red	orange	gray, violet	blue	green, yellow, white, black
violet	blue	gray	orange, red	green, yellow, white, black
white		yellow, orange	gray, green	red, violet, black, blue
yellow		green, orange, white	gray	red, violet, black, blue

Pictogram color - objective ranking

Background color	*1st e-w bin <0;0.25)*	*2nd e-w bin <0.25;0.5)*	*3rd e-w bin <0.5;0.75)*	*4th e-w bin <0.75;1>*
black		gray	violet, blue, orange	red, green, yellow, white
blue	violet	gray	orange, red, black	green, yellow, white
gray		violet, blue	orange, red, black	green, white, yellow
green		yellow, orange	gray	red, white, violet, blue, black
orange		red, gray	violet, green	yellow, blue, white, black
red	orange	gray, violet	blue, black	green, yellow, white
violet	blue	gray	orange, red, black	green, yellow, white
white		yellow	orange, gray, green	red, violet, black, blue
yellow		green, orange, white	gray	red, violet, black, blue

To identify friendly and visible combinations, as well as those quickly capturing attention, we applied the non-parametric Kruskal-Wallis test ($\alpha = 0.05$), since the data distribution deviated from normality. The analysis focused on the 3rd and 4th bins - excluding the first due to low sample count and the second due to similarity with the third. The results (z-scores) are shown in Figure 3. The 4th bin significantly outperformed others (the only one above the mean), with p-values of $8.764e^{-10}$ for subjective data (Fig. 3:Left) and 0.042 for objective data (Fig.3:Right). This confirms the effectiveness of the selected combinations in the multi-criteria analysis (Subsection5.1).

To emphasize practical implications, we also computed *effect sizes* [2], reflecting the probability that color pairs from one group outperform those from another. An ES of 50% means equal performance; higher ES indicates a greater difference. The ES between the 3rd and 4th bins showed that, subjectively, 4th-bin pairs were rated as 78.05% more friendly and visible. Objectively, they were 66.45% more eye-catching than those in the 3rd bin.

6. Discussion

The present study offers novel insights into perceptual and cognitive factors influencing message recognition on automotive displays, thereby contributing to ongoing discussions within HCI for

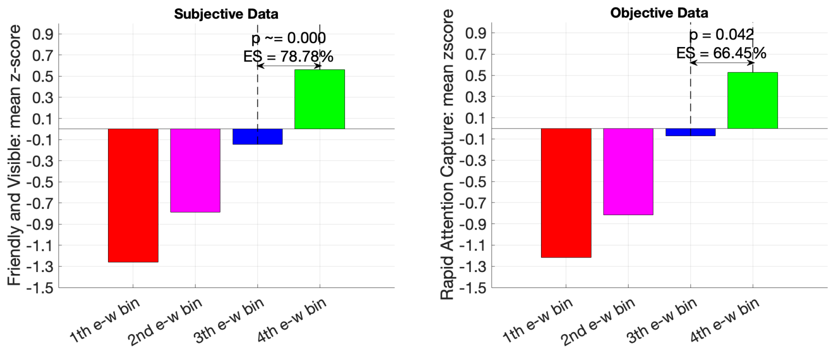

Fig. 3. Kruskal-Wallis Test and Effect Size between 3rd and 4th equal-width bin groups for subjective - Friendly and Visible (Left) and objective - Rapid Attention Capture (Right) data.

vehicle environments [11]. It addresses a recognized research gap [14] related to designing in-vehicle interfaces that enable fast and effective visual perception of dashboard messages under varying lighting conditions. Our findings emphasize the critical role of perceptual and cognitive aspects, particularly those associated with color perception, in enhancing the clarity and effectiveness of visual communication in automotive settings. These results extend the current understanding of human-vehicle interaction and lay the groundwork for developing more user-centered interface design strategies [10]. From a theoretical standpoint, the findings support a holistic design approach that integrates both perceptual and cognitive considerations, aligning with human-centered frameworks such as Kansei Engineering [9]. This perspective underscores the importance of addressing not only functional efficiency but also the emotional and subjective experiences of users, offering promising avenues for future theoretical development in automotive HCI.

The practical implications of our research are illustrated in Figure 4, which demonstrates how adapting color schemes to different lighting conditions can improve the speed and accuracy of message recognition, ultimately enhancing driver safety and comfort. These insights provide actionable guidance for designers of in-vehicle systems, helping to overcome challenges posed by diverse interface designs and mitigate driver distraction.

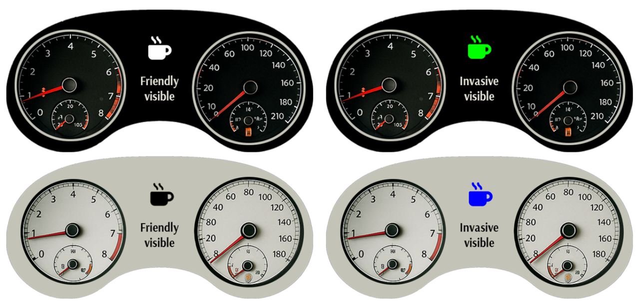

Fig. 4. Example of alert colors for dark and light modes in the car interface for Friendly and Visible (Left) and Rapid Attention Capture (Right) scenarios.

Despite these contributions, certain limitations should be acknowledged. As the study was conducted in controlled laboratory settings, its findings may not fully generalize to real-world driving scenarios. Future research should therefore build on this work by utilizing driving simulators to more comprehensively evaluate user responses, incorporating not only visual perception but also physiological metrics such as brain activity. Such an expanded approach would enrich our understanding of the complex cognitive and affective processes involved in human–vehicle interaction, supporting the creation of increasingly effective and user-centered interface designs.

7. Conclusions

This study demonstrates how perceptual and cognitive factors - particularly related to color perception - affect message recognition on automotive displays under varying lighting conditions. The findings contribute to safer, more user-centered design of in-vehicle systems and open new avenues for incorporating human-centered design approaches such as Kansei Engineering.

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