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Research Article

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Augmented Reality Windshield Displays and Their Potential to Enhance User Experience in Automated Driving

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Abstract: Increasing vehicle automation presents challenges as drivers of highly automated vehicles become more disengaged from the primary driving task. However, even with fully automated driving, there will still be activities that require interfaces for vehicle-passenger interactions. Windshield displays are a technology with a promising potential for automated driving, as they are able to provide large content areas supporting drivers in non-driving related activities. However, it is still unknown how potential drivers or passengers would use these displays. This work addresses user preferences for windshield displays in automated driving. Participants of a user study ($N = 63$) were presented two levels of automation (conditional and full), and could freely choose preferred positions, content types, as well as size, transparency levels and importance levels of content windows using a simulated "ideal" windshield display. We visualized the results in form of heatmap data which show that user preferences differ with respect to the level of automation, age, gender, or environment aspects. These insights can help designers of interiors and in-vehicle applications to provide a rich user experience in highly automated vehicles.

Keywords: windshield displays, head-up displays, user preferences, automated driving, heatmaps

1 Introduction

The provision of automated driving systems promises advantages for societies and individuals, such as increased safety, improved traffic efficiency, or mobility for the impaired [33, 8]. Still, the potentially most promising benefit for consumers is the possibility to engage in non-driving related tasks (NDRTs). Many desired activities are web-browsing, texting, or media consumption [19]. Since technological advances could soon lead to display technologies, such as windshield displays (WSDs, augmented reality head up displays that cover the whole windshield [9]), new opportunities will arise to convert vehicles into infotainment platforms [24]. However, when thinking about visionary vehicle interiors, one must consider the different levels of automation [2], that pose different requirements on driver-vehicle cooperation. For example, in SAE level 5, the vehicle is able to perform the entire dynamic driving task without any need of a human operator, while in level 3, drivers must be prepared to resume control any time, and on short notice. This issues a number of challenges to automotive user interfaces, such as increased workload or stress resulting from frequent task switching [34]. Additionally, future vehicle concepts (such as the VW I.D., the Audi Aicon, or the Mercedes F105) often show chromeless designs and allow driver-passengers to freely rotate seats, which highlights the need for new visualization and interaction concepts. WSDs could thereby become a valuable technology in the gradual transformation from semi- to fully automated vehicles ([12], [26]), as they provide various benefits: They eliminate physical and visual clutter in the center console and thereby enable gesture-based interaction [23]. Instead of having various functionalities spread around the driver's seat, WSDs can provide a single interface for all in-vehicle infotainment systems [4]. Potential dangers can be visualized directly in the field of view, what enhances safety for vulnerable road users or drivers with cognitive impairments [15]. Also, context-aware information such as displaying messages or augmenting points of interest [7], advertisements [3] or navigational aids [6] can be presented. Additionally, WSDs could allow world-fixed augmented reality visualizations that support users in the perception of the outside environment. The large interaction space of WSDs could further be utilized in side activities, and vehicles could transform

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into mobile cinemas or extended office environments [28]. However, little research has been conducted on how potential users would use these displays, which information they desire, or where content should be located. We don't know whether users accept that they have no direct perception of the outside environment (especially what is in front of the vehicle), and if semi-transparent content could help to increase acceptance in vehicle automation. We hypothesize that the answers to these questions are highly sensitive to the level of automation and/or user characteristics. To shine light on the matter, we aimed at revealing user preferences in this novel display technology and evaluate its applicability in the context of automated driving.

This paper is structured as follows: in section two we present recent research on WSDs and augmented reality in driving applications. We present our experimental design and the addressed research questions in sections three and four. Results are reported with respect to different levels of automation, content types, transparency levels, as well as age, gender and environment aspects in section five. After a rigorous discussion of the implications of our experiment (section six), we discuss potential limitations and conclude with an outlook on future work in sections seven and eight.

2 Augmented Reality Windshield Displays

In the context of manual driving, the potential of augmented reality (AR) applications has already been shown. For example, Smith et a. [30] could demonstrate that presenting information directly in a driver's line of sight can increase driving performance and diminish distraction. Approaches utilizing head-up displays (HUDs) thus often aim to increase safety. Park, Lee and Kim [18] used radar sensor information to generate enhanced forward collision warnings. A similar concept was shown by Hu et al. [10], who directly provided night-vision systems for drivers. Tangmanee and Teeravanrunyou [32] augmented the brake way of the ego vehicle to prevent crashes. Lorenz et al. [16] supported the driver with augmented reality scenario information during the transition from automated to manual driving to increase their situation awareness. In the future, WSDs could support cooperative, intelligent transportation systems (C-ITS), that dynamically adjust road configurations to maximize throughput, by providing dynamic, real-time visualizations of traffic signs, lane markings, etc. [25].

Applications using WSDs are expected to improve in-vehicle experiences and ease the implementation of automated vehicles in the transition phase [12]. However, because of technical but also cost issues, WSDs have not yet been developed. According to Gabbard et al. [4], this could become the greatest hurdle preventing their utilization in the near future. Currently, AR-HUDs face problems like change blindness [20], or limited interaction space and field of view. Future technologies, such as optical see through light-field displays [14] could eliminate these problems and finally allow WSDs that cover the entire windshield.

The drivers' preferences when it comes to automated driving have already been explored, however, mostly regarding trust and acceptance of the technology in general. For example, users would use the time spent on NDRTs on working, reading, and playing games [17]. We intend to go a step further by letting the potential users choose what content should be placed at the WSD and how it should behave in terms of transparency, size etc. In the meantime, the potential of WSDs can be demonstrated and evaluated using software simulation. Häuslschmid et al. [7] developed a generalizable view management for manual vehicles that considers drivers' tasks, context, resources, and abilities for efficient information recognition and comprehension. They proposed zones and areas for specific information types, ranging from pre-attentive and safety-critical messages, to attentive, less critical information such as personal email. The presented view management proposes certain areas for specific information, such as personal information, vehicle information, warnings etc. [7] We chose to eliminate all potential restrictions of such settings, and designed an experiment aiming to reveal driver-passengers' requirements and preferences in WSDs, and thereby distinguished between different content types and levels of automation.

3 User Study

3.1 Method and Research Questions

To evaluate how AR WSDs can be utilized in highly automated vehicles, as well as by whom and in what situation content should be displayed on the WSD, we performed a user study. We wanted to investigate the following research questions:

- **RQ1:** Which, and how many areas on WSDs do drivers of automated vehicles prefer for displaying information?

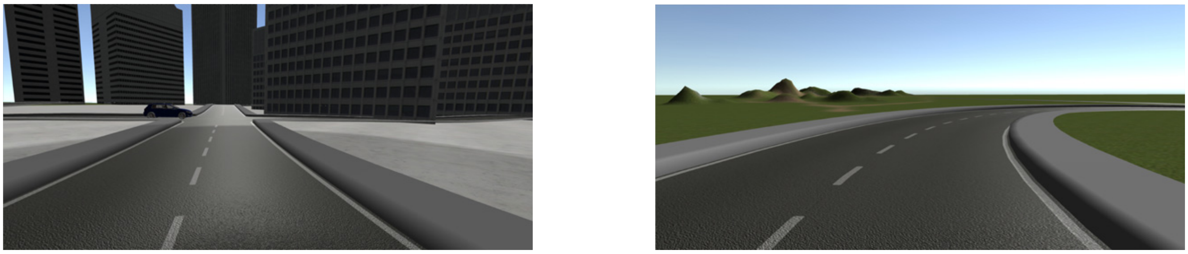
- **RQ2:** How does the level of automation (conditional, full) influence drivers' preferences?
- **RQ3:** Which size and format (widescreen, portrait) of content areas is desired?
- **RQ4:** Is there a hidden agreement on the display location of types of in-vehicle information (vehicle-related, trip-related, entertainment, etc.)?
- **RQ5:** Which level of background transparency of content areas is desired?
- **RQ6:** Are certain content types perceived as more important than others?
- **RQ7:** Does gender influence drivers' preferences?
- **RQ8:** Does age influence drivers' preferences?
- **RQ9:** Does the driving environment (highway, urban) influence drivers' preferences?

Our study setting enables users to freely set the position, size, transparency and importance of multiple content windows (represented as rectangles) on a WSD. We choose to conduct our evaluation on a two-dimensional display, since mixed display distances can have a negative impact on performance [31], and we wanted to design the study setting as simple as possible. With assistance of our experimenters, participants were asked to draw multiple rectangles on the WSD (see Figure 1) according to their personal preferences, and afterwards associate each content area with different types of information (e. g. warnings, vehicle-related information, entertainment, social media, etc.) as well as the background transparency and importance. We decided to use rectangles as content windows only as this shape is most commonly used in applications in many domains, such as desktop computers, tablets, or smartphones. Further, demographic data and survey questions related to WSDs and automated driving were obtained. Both the demographic questionnaire and the survey were presented to the participants on a tablet computer. In addition, our experimenters were constantly observing the participants' remarks and, using the laddering technique, tried to ascertain further information about participants' motives and notions.

Figure 1: The study setting, a 55" flat screen monitor and a computer mouse for drawing and placing the content windows.

3.2 Experimental Design

For conducting the experiment we created two three dimensional scenes in Unity3D, that show the interior of a right-hand driven BMW i8 from the driver's perspective. For the level 5 scenario we modified the cockpit by removing the steering wheel as well as the gear shift to emphasize that the driver cannot take over the vehicle, as opposed to the level 3 scenario. Either model was then placed on a highway road and on a city crossing surrounded by skyscrapers (see Figures 2a and 2b). We set the scene as background image and used a drawing application (with a custom view consisting of only necessary tools, such as the possibility to draw rectangles) as interface for the experiment. While this static setup is technically simple, the solution has multiple benefits. First, the drawing application is well known and widely used, thus we did not have to explain the process of drawing to our participants, and second, it easily allowed to group the different rectangles, what eased evaluation and subsequent heatmap generation. The application was then displayed to participants



(a) City scene.

(b) Highway scene.

Figure 2: 3D environments for situational analysis (vehicle interior not displayed).

in fullscreen/borderless mode on a 55” flat screen monitor with a resolution of 3840x2160px (see Figure 1).

3.3 Procedure

First, participants had to complete a short demographic questionnaire, including age, gender, highest level of education, if they possess a valid driving license, and the approximate covered annual vehicle volume (driven by them). We explained conditional and fully automated driving. For the conditional driving scenario we told participants that situations where the driver has to actively take control of the vehicle can arise at any time. For the fully automated driving scenario, we noted that the vehicle cannot be controlled by the driver in any way, which was underlined by the lack of a steering wheel and gear shift in the visualization of the vehicle’s cockpit. We further explained the concept of a windshield display and emphasized the precedence of a safe but also comfortable drive. Additionally, we told participants to imagine sitting alone in the vehicle, and that the vehicle is their own (i. e., no public transport vehicle with strangers). Then, participants were presented the drawing application, and we asked them to draw multiple rectangles within the boundaries of the WSD according to their preferences. For each window, participants had to specify the desired content type (by drag and drop). According to a study conducted by McKinsey [17], drivers have certain preferences for activities in automated vehicles. Therefore, we offered a list containing potential content types:

- *Warnings (**W**)*, such as a potentially short headway, mechanical failures, etc.
- *Vehicle information (**V**)*, such as the current speed, or distance/time to destination
- *Work/office related information (**O**)*, such as emails or calendar
- *Entertainment (**E**)*, such as music playlists, videos, etc.
- *Social Media (**S**)*, such as Facebook, Twitter, etc.
- *Custom/Other (**C**)*, such as weather information, smarthome control, etc.

It was allowed to overlap windows and there was no requirement to use all content types, and a single content type could be assigned multiple times if desired. In case a participant wanted to display multiple content types inside a single rectangle, we counted this as two different windows in our evaluation. For example, if a participant wanted to see both social media, as well as work-related content, in one and the same rectangle (“content window”), we regarded this as two windows with one being dedicated to social media, and the other to office/work. For each content window, participants were asked to set its background transparency using a slider. Additionally, participants had to specify which content windows they perceived as more important than others, by dragging their layers in the desired order (top was higher importance/priority). This procedure was performed twice, for both conditions level 3 and level 5 driving (in randomized order). Therefore, each participant was exposed to a total of two conditions, e. g. the level 3 city scenario and the level 5 highway scenario. Before each condition we explained the corresponding level of automation to participants. After both conditions, participants had to complete a short post-questionnaire on a tablet. This survey aimed to get insights about participants’ attitude towards WSDs and AR in driving automation. The experiment lasted approximately 30 minutes for each participant.

4 Results

In total, 63 people (44 male, 19 female) between 17 and 81 (37 + / − 19.7) years participated in the experiment (all possessing a valid driver’s license). In our university, we recruited students, researchers, and teaching assistants. Additionally, we invited external people to take part in our study while attending information days about the university. For recruiting elderly participants, we organized a “senior citizen day” at our university, where we also explained the concept of automated vehicles, as well as future interaction possibilities with vehicles. All participants were from Central Europe. Because of the age heterogeneity, we created a simple study setup that all participants could use with ease.

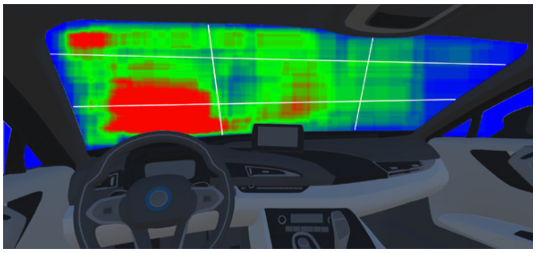
Statistical results presented were conducted using IBM SPSS Version 24 with a significance level of $p < .05$. Not all of our data was normally distributed, and since the sample size of the different content types was not equal, we conducted pairwise comparisons utilizing Wilcoxon signed rank tests for within-subjects effects, and Mann-Whitney U tests for between subjects evaluations, both with Bonferroni correction for alpha-adjusted significance levels.

In the following, we present a detailed investigation of the obtained results. In section 4.1, we describe general findings in WSD preferences between level 3 and level 5 automation, and visualize them with heatmaps. We further take an in-depth look at the different content types and their usage in section 4.2. Additionally, we look at window parameters, such as transparency (section 4.3) and importance (section 4.4). Moreover, we investigate user preferences depending on participants' age (section 4.5), gender (section 4.6) and the environment (section 4.7). Finally, we reveal insights into the qualitative feedback from our participants (section 4.8) and their survey responses (section 4.9).

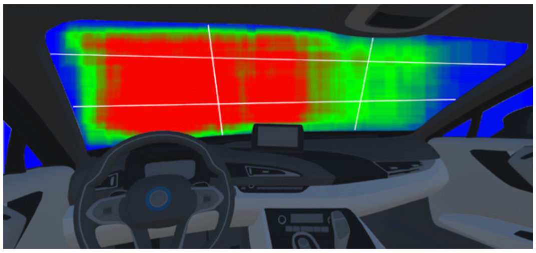
4.1 Window Characteristics and Heatmaps

On average, participants utilized 3.59 (*Std* = 1.41) content windows in level 3, and 4.29 (*Std* = 1.68) content windows in level 5 driving. The difference is statistically significant at $p = .001$. The window format (based on divergence to a square) was strongly in favor of landscape (*L*3 = 197, *L*5 = 230 counts) compared to portrait (total numbers: *L*3 = 29, *L*5 = 40 counts).

Figures 3a and 3b show the heatmaps generated from the aggregated data. Based on the drawn windows, we generated heatmaps. Overlapping windows are displayed by color gradients from green to red (red means more overlapping windows at the respective location), blue areas indicate that no window was placed at the respective location. Using this visual technique, it is instantly possible to see the main difference between level 3 and level 5 automation: The requirement to be able to take control of the driving task in conditionally automated vehicles made many participants avoid to place information in the direct line of sight (with one exception: warnings). Also, content was often placed in the imagined extension of the middle console or on the top left corner of the WSD (Figure 3a). In contrast, in the level 5 driving scenario, participants placed content windows all over the WSD, mostly in the driver's foveal area. Considering the window dimensions as specified by participants shows, that in level 5 the average size (*Mean* = 249937, *Std* = 324671 square pixels) was nearly twice as high than in level 3 (*Mean* = 131403, *Std* = 160796 square pixels) driving and showed also greater variance (see Figure 3b). We further take an in-depth look at the different content types in section 4.2.



(a) Level 3 heatmap.



(b) Level 5 heatmap.

Figure 3: Resulting heatmaps based on the aggregation of the individual content windows for level 3 and 5 automated driving scenarios.

4.2 Content Types

Additionally, we created different heatmaps for the individual content types and also counted their occurrences in different areas of the WSD. Each window was assigned to one out of 9 different locations, i. e. top, center, bottom and driver (left), middle and passenger (right) side, based on its center point belonging to the corresponding location, distorted to fit the camera projection. Figures 3a and 3b show the grid ranging over the entire WSD. Table 1 displays the number/share of windows for each content type. We further calculated the share (percentage) of the windows belonging to a corresponding content type in relation to the total size of all windows used. In level 3 driving, warnings (**W**) and vehicle-related dashboards (**V**) were not only the most-used content types, they also received the (relatively) largest space (around 30 %).

Considering the average total size of the different content types' drawn windows (see Table 2 for descriptive statistics), pairwise comparisons with an alpha-adjusted significance level of $.00\overline{3}$ show only one significant effect for level 3 driving: warnings (**W**) were significantly larger than vehicle-related dashboards (**V**, $p < .001$).

Level 5 automation shows a clear distinction: in this case, warnings were used less. Although, for example, the total number of vehicle-related dashboards **V** was similar to level 3 driving, the size of their windows was smaller. Contrarily, entertainment (**E**), work-related (**O**), and social media (**S**) content was desired more by the participants with more than 80 % of the total interaction space used (see Table 1). In level 5 driving, various differences could be evaluated. Not only warnings (**W**, $p < .001$), also work-related (**O**, $p < .001$), entertainment (**E**, $p < .001$), and social media windows (**S**, $p < .001$) were significantly larger than vehicle-related dashboards (**V**). Overall, the share of the total size roughly corresponds to the percentage of the

Table 1: Comparison of the different content types and their counts specified by participants.

	Content Type	W	V	O	E	S	C
Level 3 $N = 226$	Counts / Percentage	64 28,32 %	59 26.11 %	38 16.81 %	38 16.81 %	23 10.18 %	4 1.77 %
	Share of total size	29.09 %	16.08 %	17.21 %	24.34 %	11.82 %	1.46 %
Level 5 $N = 270$	Counts / Percentage	43 15.93 %	61 22.59 %	53 19.63 %	56 20.74 %	49 18.15 %	8 2.96
	Share of total size	10.96 %	7.62 %	23.37 %	34.94 %	20.83 %	2.28 %

Table 2: Comparison of the different content types and their sizes specified by participants.

	Content Type	W	V	O	E	S	C
Level 3 $N = 226$	Mean Size (Sq pixels)	134975	80959	134487	190199	152612	108470
	Std (Sq pixels)	124131	79074	135354	282150	157715	67730
Level 5 $N = 270$	Mean Size (Sq pixels)	172019	84308	297575	421026	286852	192357
	Std (Sq pixels)	249429	61885	307664	456418	324182	194140

window counts. In the following, we give further insights into the different content types.

Warnings (**W**) have been utilized more often in level 3, compared to level 5 driving ($L3 = 64$, $L5 = 43$). In both levels, they were prominently placed in the field of view of the driver (see Figures 4a, 4b).

Vehicle-related dashboards (**V**) have been placed just above the steering wheel in level 3, a location already utilized by available head-up displays (Figure 4c). Additionally, the top driver side of the WSD is a location often utilized for this content type. This also applies to level 5 driving (Figure 4d). Although the number of windows for this content type is nearly equal in both conditions ($L3 = 59$, $L5 = 61$), the importance drastically differs between the autonomy levels. In level 3, (**V**) accounts for about 16 % of the total area used, while in level 5 less than 8 % of the space was reserved for this content type (see Table 1).

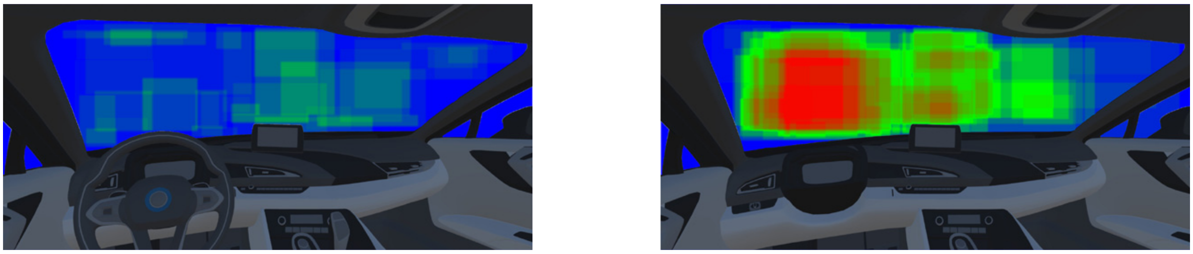
Larger differences between the levels of automation become visible when considering windows for non-driving related tasks. The three content types office/work **O**, entertainment **E**, and social media **S** were not placed prominently in the drivers field of view in level 3 driving, but more in the peripheral areas from the driver's point of view (see Figures 4e, 4g, 4i). Participants have put them mainly in the center (vertical extension of center console) and partly on the passenger's side. Also the size of the windows for these content types was relatively small compared to level 5. In level 5, office/work and entertainment content was placed directly on the driver's side in large windows – entertainment content even larger, ranging nearly across the whole WSD (see Figure 4h). Windows displaying social-media feeds/activities (**S**) were utilized more often in level 5 driving ($L3 = 23$, $L5 = 49$). In contrast to entertainment and office/work windows, participants chose various locations on the drivers, center, and passenger side for social media related information (see Figure 4j). Custom content (**C**) has been scarcely utilized ($L3 = 4$, $L5 = 8$), therefore we do not present heat maps for this content type. Regarding differences between the number of windows placed for conditional and full automation, we found that in full automation, significantly more windows were drawn. Since there is no take-over requirement for fully automated vehicles, and "drivers" can take advantage of not having to pay attention to the primary driving task, this result seems legitimate. Additionally, we looked at inter-level differences between the average total size of content windows. We found significant differences between the window size of work-related, and entertainment windows (**O**: $p < .001$, **E**: $p < .001$) using Wilcoxon signed rank tests; larger windows in level 5 automation. However, there are no statistical differences in window sizes for the other content types (however social media content **S**, $p = 0.13$ was just slightly above the adjusted significance level of $.008\overline{3}$). In other cases, the windows are similarly dimensioned for both levels of automation.

(a) Level 3 heatmap displaying warning windows (**W**).

(b) Level 5 heatmap displaying warning windows (**W**).

(c) Level 3 heatmap displaying vehicle-related windows (**V**).

(d) Level 5 heatmap displaying vehicle-related windows (**V**).



(e) Level 3 heatmap displaying work-related windows (**O**).

(f) Level 5 heatmap displaying work-related windows (**O**).

(g) Level 3 heatmap displaying entertainment windows (**E**).

(h) Level 5 heatmap displaying entertainment windows (**E**).

(i) Level 3 heatmap displaying social media windows (**S**).

(j) Level 5 heatmap displaying social media windows (**S**).

Figure 4: Heatmaps for level 3 (left) and level 5 (right) automation.

4.3 Transparency

Using a slider, participants were able to set their preferred opacity level for each drawn window. Minimum was an opacity of 0 % (transparency = 100 %), maximum was an opacity of 100 % (transparency = 0 %). The default opacity value was 100 % in order for the participants to fully see the window(s) they are drawing.

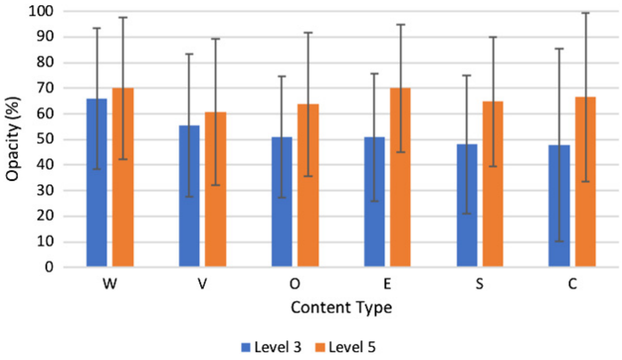


Figure 5: Transparency preferences for each content type for level 3 (blue) and level 5 (orange) automation.

Figure 5 shows the transparency results for level 3 and level 5 automation for each content type. In both levels, warning windows (**W**) received the highest opacity. Since there was an unequal number of data points (not each participant utilized each content type), we performed only pairwise comparisons using Wilcoxon signed rank tests with an alpha adjusted significance level of $.00\overline{3}$. In level 3 driving only two comparisons yielded to significant effects: warnings **W** had higher opacity than vehicle-related dashboards **V** ($p = .002$) and work-related content windows **O** ($p = .002$). For level 5 driving, no such difference could be evaluated.

When comparing inter-level differences in windows transparency using Wilcoxon signed rank tests, we found that level 5 work-related content (**O**), entertainment (**E**) and social media content (**S**) received a statistically significant higher opacity than their counterparts in level 3 (**O**: $p = 002$, **E**: $p < .001$, **S**: $p = .003$). We believe that since take-over requests are not needed or even possible in fully automated driving, "drivers" tend to focus on in-vehicle activities such as reading emails, watching movies etc. which require less transparent windows.

Furthermore, we wanted to find out if there is a correlation between the parameters area and transparency. We did not find relevant area-transparency correlations for level 3 automation. However, for the level 5 scenario, we found weak positive correlations for the content types work-related content, entertainment and social media content (**O**: $\rho = 27.9\,\%$, **E**: $\rho = 30.8\,\%$, **S**: $\rho = 27.1\,\%$). In these cases, larger windows were attributed with a higher opacity by the participants.

4.4 Importance

We further investigated the importance resp. priority for each drawn window. Participants were able to subjectively rate their drawn windows. The highest priority was 1, the maximum priority was determined by the number of windows and it was possible to rate windows as equal. This procedure was done by the participant or experimenter by dragging the window layers on the right side of the screen into the desired order.

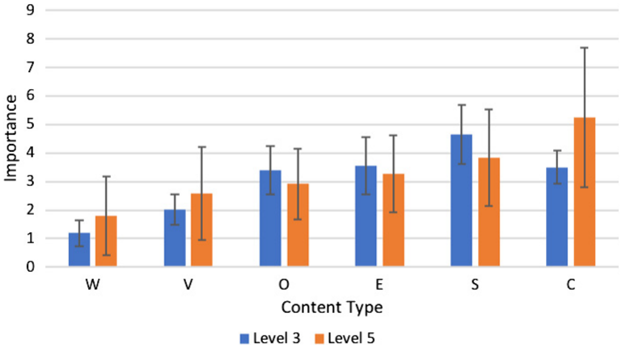


Figure 6: Importance preferences for each content type for level 3 (blue) and level 5 (orange) automation (lower values represent higher priority).

Figure 6 shows the subjectively given importance results for level 3 and level 5 for each content type. Lower scores are better/indicate a higher subjective priority. One can instantly see that warnings received the highest importance for both level 3 and level 5 driving. Since also here the number of data points for each content type varies we again conducted pairwise comparisons using Wilcoxon signed rank tests with an alpha-adjusted significance level of $.00\overline{3}$. Warnings **W** were rated to be significantly more important than vehicle-related dashboards **V** ($p < .001$), work-related content **O** ($p < .001$), entertainment windows **E** ($p < .001$), and social media content **S** ($p < .001$). Vehicle-related dashboards **V** were significantly more important than work-related content **O** ($p < .001$), entertainment **E** ($p < .001$), and social media windows **S** ($p < .001$), and finally work-related content **O** was more important than social media **S** ($p = .002$).

In level 5 driving we obtained a similar result: warnings **W** were more important than vehicle-related dashboards **V** $p < .001$, entertainment **E** ($p = .001$), and social media windows **S** ($p < .001$); work-related content **O** was rated to be more important than social media **S** ($p = .002$). Regarding the inter-level difference between the content types and their perceived importance (based on an alpha adjusted significance level of $.008\overline{3}$), warnings (**W**, $p = .003$) and vehicle-related dashboards (**V**, $p = .002$) received a significantly higher priority in level 3 than in level 5. No other differences between the level of automation could be evaluated.

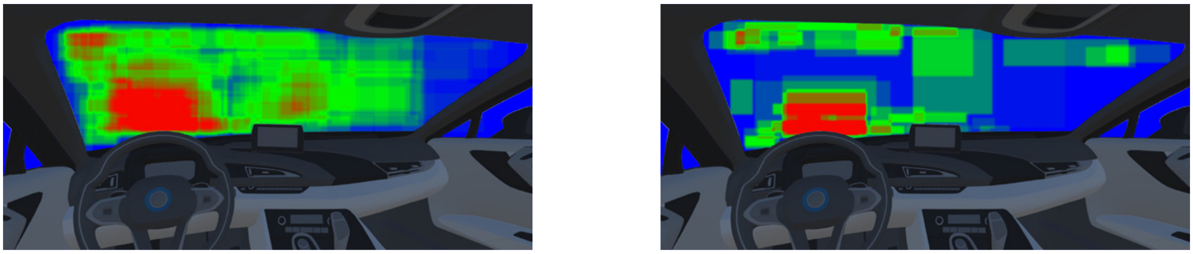
Furthermore, we wanted to find out if there is a correlation between the parameters transparency and importance. For level 3 automation, we found a weak positive correlation between the transparency of social media windows and their subjectively rated importance ($\rho = 30.0\,\%$), i. e. the more opaque the window, the higher its importance as stated by the participants. We did not find any other relevant transparency-importance correlations for level 3 automation. However, for the level 5 scenario, we calculated weak positive correlations for the content types work-related content, entertainment and social media content (**O:** $\rho = 26.7\,\%$, **E:** $\rho = 29.3\,\%$, **S:** $\rho = 27.0\,\%$).

Additionally, we wanted to find out if there is a correlation between the parameters area and importance. For warnings, there is a weak positive correlation between their area and subjective importance ($\rho = 22.3\,\%$) in level 3 automation. This means that larger windows are seen as more important. This is similar to vehicle-related dashboards ($\rho = 24.5\,\%$). In contrast, the areas of work-related content, entertainment and social media content were moderately negatively correlated with their perceived importance (**O:** $\rho = -43.5\,\%$, **E:** $\rho = -30.6\,\%$, **S:** $\rho = -19.4\,\%$). This may be because these content types are not well suited for conditional automation because of potential take-over tasks at any point in time. For level 5 automation, the parameters area and importance are very weakly correlated ($|\rho| < 20\,\%$).

4.5 Age Specific Differences

We further separated the participants in two groups, 47 younger drivers (*Mean* = 27, *Std* = 6.1) and 16 elderly drivers (*Mean* = 69, *Std* = 8.9) to investigate potential differences in their WSD preferences. Figure 7 displays the overall results for level 3 and level 5 driving, differentiated by young and elderly drivers, respectively.

While in level 3 driving, young drivers prefer content windows to be positioned all over the windshield, most prominently in the driver's direct field of view, elderly drivers tend to place their content windows mostly in the direct field of view and the top part of the windshield display. In level 5 driving, young participants chose the entire windshield display for their content windows, while elderly participants utilized the windshield display more sparingly.



(a) Level 3 heatmap generated from young drivers' preferences.

(b) Level 3 heatmap generated from elderly drivers' preferences.

(c) Level 5 heatmap generated from young drivers' preferences.

(d) Level 5 heatmap generated from elderly drivers' preferences.

Figure 7: Heatmaps for level 3 (top) and level 5 (bottom) automation; differentiated by young (left) vs. elderly (right) drivers.

(a) Heatmap displaying warning windows (**W**) according to young drivers.

(b) Heatmap displaying warning windows (**W**) according to elderly drivers.

(c) Heatmap displaying vehicle-related windows (**V**) according to young drivers.

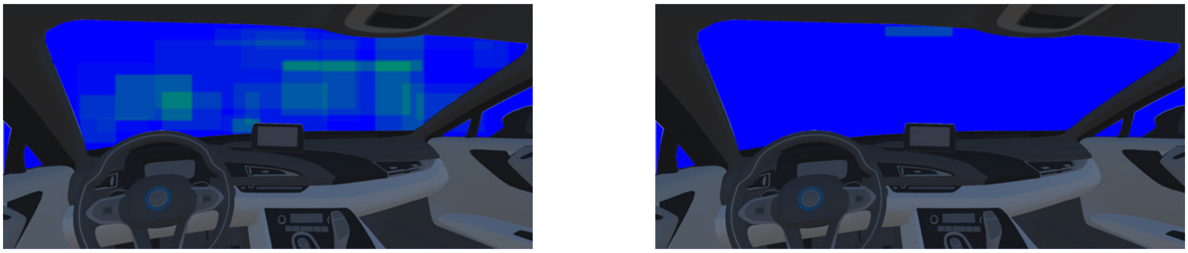
(d) Heatmap displaying vehicle-related windows (**V**) according to elderly drivers.

(e) Heatmap displaying work-related windows (**O**) according to young drivers.

(f) Heatmap displaying work-related windows (**O**) according to elderly drivers.

(g) Heatmap displaying entertainment windows (**E**) according to young drivers.

(h) Heatmap displaying entertainment windows (**E**) according to elderly drivers.



(i) Heatmap displaying social media windows (**S**) according to young drivers.

(j) Heatmap displaying social media windows (**S**) according to elderly drivers.

Figure 8: Level 3 heatmaps displaying the WSD preferences for young (left) and elderly (right) drivers.

(a) Heatmap displaying warning windows (**W**) according to young drivers.

(b) Heatmap displaying warning windows (**W**) according to elderly drivers.

(c) Heatmap displaying vehicle-related windows (**V**) according to young drivers.

(d) Heatmap displaying vehicle-related windows (**V**) according to elderly drivers.

(e) Heatmap displaying work-related windows (**O**) according to young drivers.

(f) Heatmap displaying work-related windows (**O**) according to elderly drivers.

(g) Heatmap displaying entertainment windows (**E**) according to young drivers.

(h) Heatmap displaying entertainment windows (**E**) according to elderly drivers.

(i) Heatmap displaying social media windows (**S**) according to young drivers.

(j) Heatmap displaying social media windows (**S**) according to elderly drivers.

Figure 9: Level 5 heatmaps displaying the WSD preferences for young (left) and elderly (right) drivers.

In level 3 driving, young participants utilized 3.9 content windows on average (*Std* = 1.40), while elderly drivers only placed 2.7 content windows (*Std* = 1.01). The difference is statistically significant ($p = .002$). In level 5 driving, young participants averaged 4.8 windows (*Std* = 1.45), and elderly participants used 2.9 windows (*Std* = 1.54). In the level 5 scenario, this difference is also significant ($p < 0.001$).

Regarding the area of content windows in level 3 driving, young participants used larger areas for all content types. In contrast, in level 5 driving, elderly participants choose larger content windows for vehicle-related dashboards (**V**). However, we did not find any significant differences in both scenarios utilizing Mann-Whitney U tests.

Even though elderly drivers preferred all their content windows to be less transparent than their younger counterparts, the use of transparency did not show any significant differences in the level 3 driving scenario. In contrast, elderly participants chose less transparent windows for various content types (**V**: $p = 0.023$, **O**: $p = 0.029$, **E**: $p = 0.02$, **S**: $p = 0.017$) in level 5 driving. However, these differences are only tendencies and do not match the alpha-adjusted significance level of $.008\overline{3}$.

Furthermore, in level 3 driving, we found that elderly participants prioritized work-related content (**O**) significantly higher than younger drivers ($p = .006$), while in the level 5 scenario, elderly participants rated both work-related (**O**, $p = .005$) and vehicle-related content (**V**, $p = .007$) to be more important. Other significant differences could not be assessed.

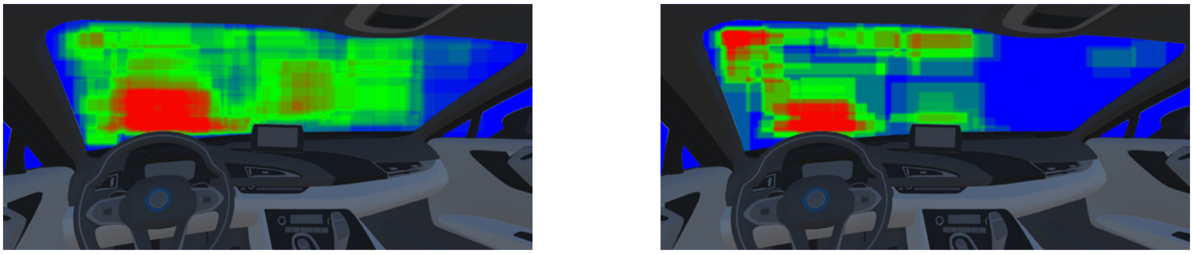
Figures 8 and 9 show the level 3 and level 5 heatmaps for each content type, with the distinction for the age of the drivers, i. e., younger vs. elderly drivers.

4.6 Gender Specific Differences

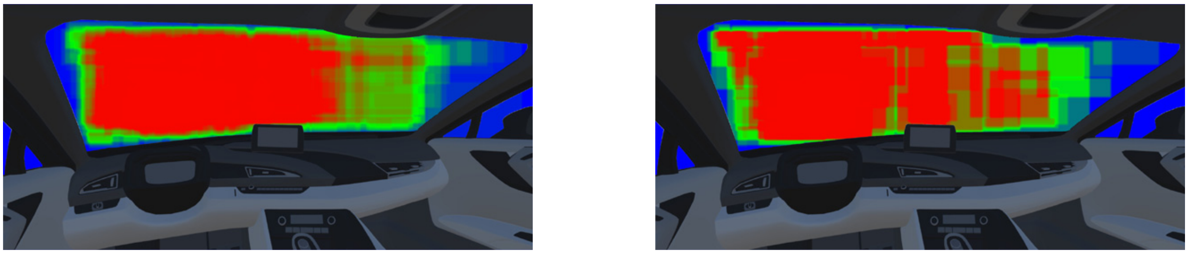
We additionally investigated the role of gender in automated driving and their differences in WSD preferences. Figure 10 displays the overall results for level 3 and level 5 driving, differentiated by male and female drivers, respectively.

For level 3 driving, one can instantly see differences in male and female preferences for window placements. While male participants prominently placed content in the driver's field of view, and additionally utilizing large parts of the WSD (see heatmap 10a), female participants focused their content windows in the bottom as well as the top (left and center) areas of the WSD (see heatmap 10b). Regarding level 5 driving, both male and female participants utilized almost the entire WSD (see Figures 10d and 10c).

In level 3 driving, male participants utilized 3.8 content windows on average (*Std* = 1.47), while females only placed 3.1 content windows (*Std* = 1.13). The difference is significant ($p = 0.045$) considering a Mann-Whitney U test. In level 5 driving, male participants averaged 4.4 windows (*Std* = 1.46), and female participants used 4.1 windows



(a) Level 3 heatmap generated from the male drivers' preferences. **(b)** Level 3 heatmap generated from the female drivers' preferences.



(c) Level 5 heatmap generated from the male drivers' preferences. **(d)** Level 5 heatmap generated from the female drivers' preferences.

Figure 10: Heatmaps for level 3 (top) and level 5 (bottom) automation; differentiated by male (left) vs. female (right) drivers.

(*Std* = 2.13). In the level 5 scenario, this difference is not statistically significant.

Regarding the area of content windows in level 3 driving, male participants used slightly larger areas for the content types except for social media content (**S**), however, no statistically significant differences could be evaluated. In contrast, in level 5 driving, female participants choose larger content windows for work-related content (**O**) and social media content (**S**). However, we did not find any significant differences in this scenario using Mann-Whitney U tests considering the significance level of $.08\overline{3}$.

Also the use of transparency or importance did not show any significant differences for the proposed content types for male and female participants in both levels of automation.

Figures 11 and 12 show the level 3 and level 5 heatmaps for each content type, with the distinction for the gender, i. e., male vs. female preferences.

4.7 Environment Related Differences

We further looked into differences that might arise from driving in changing environments. Therefore, we created a city and a highway scene. Figure 13 displays the overall results for level 3 and level 5 driving in the city scene and the highway scene, respectively. While both level 5 heatmaps do not show clear distinctions (see Figures 13c and 13d), it is evident that drivers had different WSD preferences in the city and on the highway in level 3 driving. While heatmap 13a (city scene) shows that drivers do not prefer to occlude the direct field of view by placing content windows in the peripheral areas, heatmap 13b (highway scene) shows that participants prominently placed content windows on the driver's side of the WSD.

In level 3 driving, participants utilized 3.5 content windows on average (*Std* = 1.52) in the city environment, while they placed 3.7 content windows (*Std* = 1.32) in the highway scene. In level 5 driving, participants averaged 4.4 windows (*Std* = 1.62), and female participants used 4.1 windows (*Std* = 1.76). In both levels of automation, the difference is not statistically significant.

Regarding the area of content windows in level 3 driving, participants utilized similar-sized areas for all content types in both the city and the highway scene. This is also the case for the level 5 driving scenario.

The use of transparency did not show any significant differences for the proposed content types in both environments in the level 3 driving scenario. However, the chosen transparency was in all cases larger in the highway scene as opposed to the city environment. Similarly to the level 3 scenario, participants chose less transparency for all content windows on average for the highway environment in level 5 driving. Also here the difference is not statistically significant considering the alpha-adjusted significance level of $.008\overline{3}$. However, there is some tendency, that participants chose less transparent windows for the content types warnings (**W**, p = .039), entertainment (**E**, p = .067) and social media (**S**, p = .057).

Furthermore, in level 5 driving, descriptive statistics indicate, that participants perceived warnings as more important in the city than in the highway scenario. Further, content windows were rated as generally more important in the city than in the highways scene. However, considering the statistical evaluation, these assumptions are not supported by the results of conducted Mann-Whitney U tests.

Figures 14 and 15 show the level 3 and level 5 heatmaps for each content type, with the distinction for the scenery, i. e., city vs. highway preferences.

4.8 Qualitative Feedback

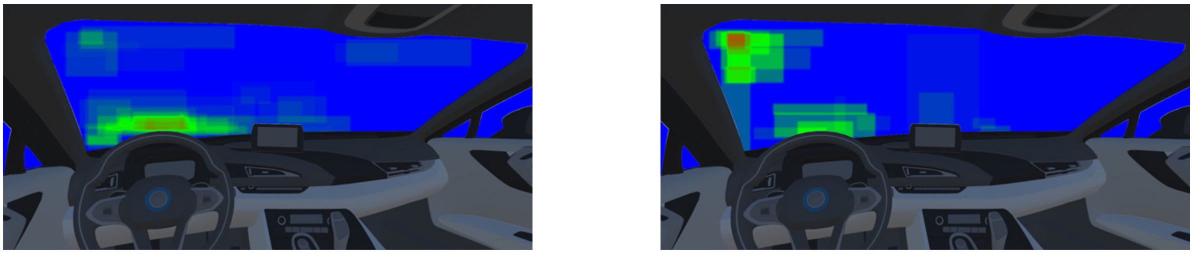
During the experiments, our experimenters were constantly taking notes about the participants opinion and verbal statements. Whenever participants would make remarks about drawing, placing windows or assigning content types, experimenters would use the laddering technique to extract further and more detailed information to gain a more comprehensive insight into the use of AR WSDs. We analyzed the qualitative data by categorizing the experimenters' observations of the participants' remarks by looking for patterns or common themes emerging around the concept of AR WSDs and automated driving. Based on these observations, we extracted the following key points:

4.8.1 View Management

Approximately one third of participants wanted to utilize the same space on the WSD for multiple different contents. For example, entertainment and work-related windows were often grouped together, and, based on the situation, should either show entertainment content (e. g., a movie) or work-related content (e. g., a task list, emails). Additionally, participants also stated that a separate section of the WSD for the front passenger would make sense (e. g., passenger watching a movie on the passenger WSD side, while the driver observes vehicle-related information on his side). Therefore, a dynamic window management

(a) Heatmap displaying warning windows (**W**) according to male drivers.

(b) Heatmap displaying warning windows (**W**) according to female drivers.

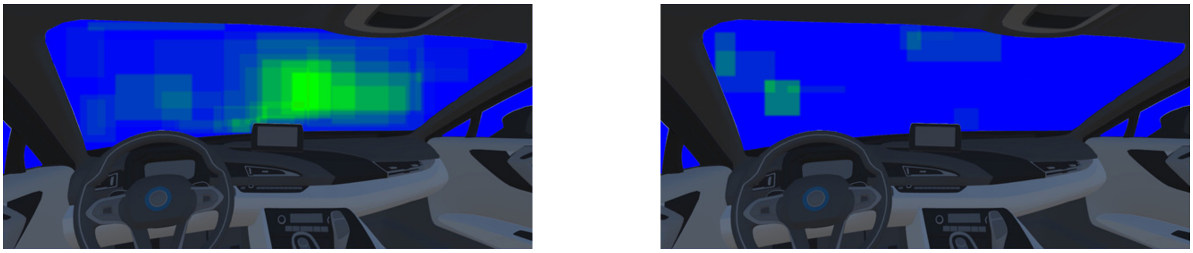


(c) Heatmap displaying vehicle-related windows (**V**) according to male drivers.

(d) Heatmap displaying vehicle-related windows (**V**) according to female drivers.

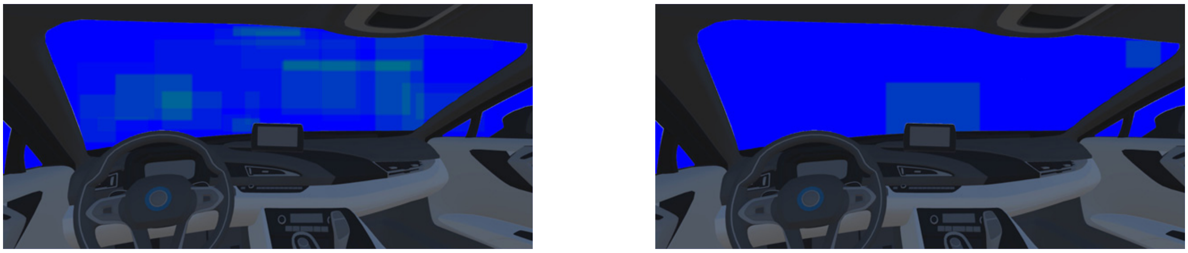
(e) Heatmap displaying work-related windows (**O**) according to male drivers.

(f) Heatmap displaying work-related windows (**O**) according to female drivers.



(g) Heatmap displaying entertainment windows (**E**) according to male drivers.

(h) Heatmap displaying entertainment windows (**E**) according to female drivers.



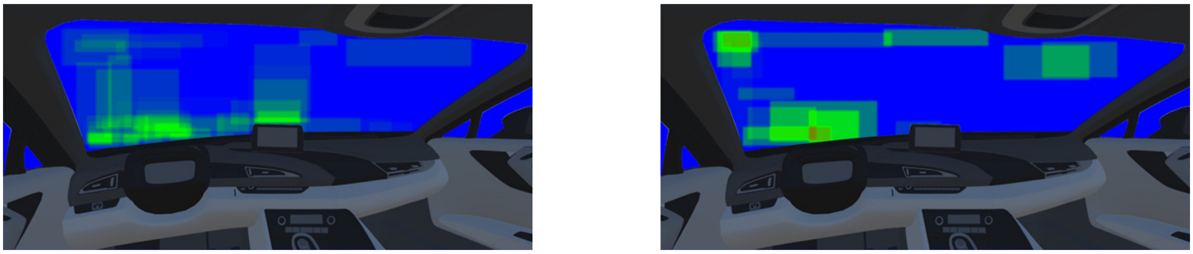
(i) Heatmap displaying social media windows (**S**) according to male drivers.

(j) Heatmap displaying social media windows (**S**) according to female drivers.

Figure 11: Level 3 heatmaps displaying the WSD preferences for male (left) and female (right) drivers.

(a) Heatmap displaying warning windows (**W**) according to male drivers.

(b) Heatmap displaying warning windows (**W**) according to female drivers.

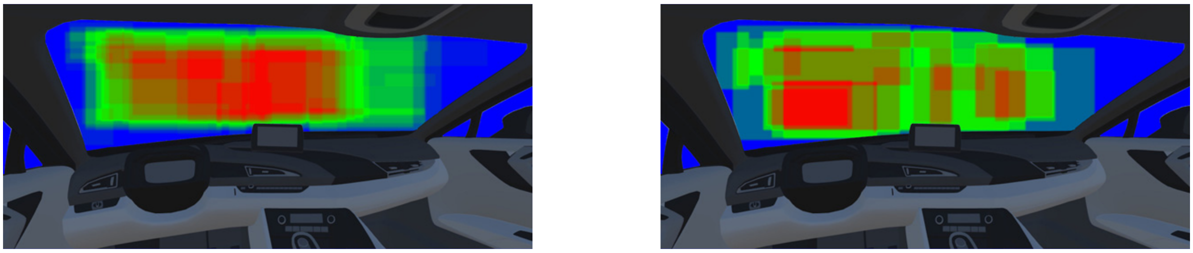


(c) Heatmap displaying vehicle-related windows (**V**) according to male drivers.

(d) Heatmap displaying vehicle-related windows (**V**) according to female drivers.

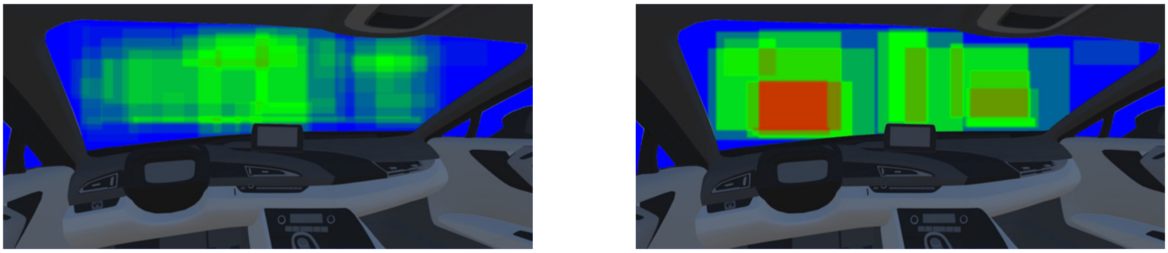
(e) Heatmap displaying work-related windows (**O**) according to male drivers.

(f) Heatmap displaying work-related windows (**O**) according to female drivers.



(g) Heatmap displaying entertainment windows (**E**) according to male drivers.

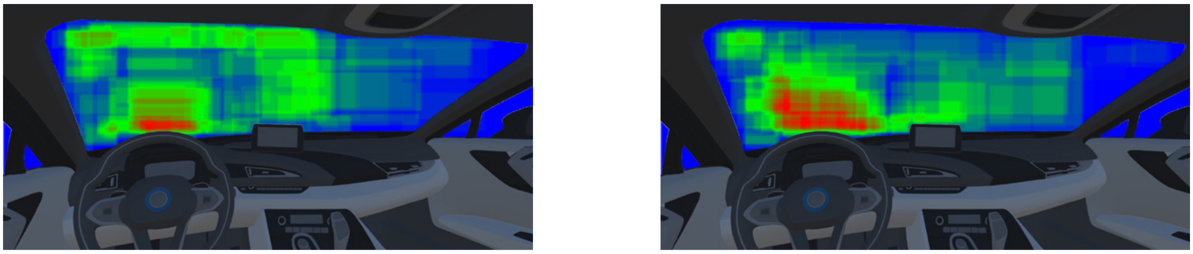
(h) Heatmap displaying entertainment windows (**E**) according to female drivers.



(i) Heatmap displaying social media windows (**S**) according to male drivers.

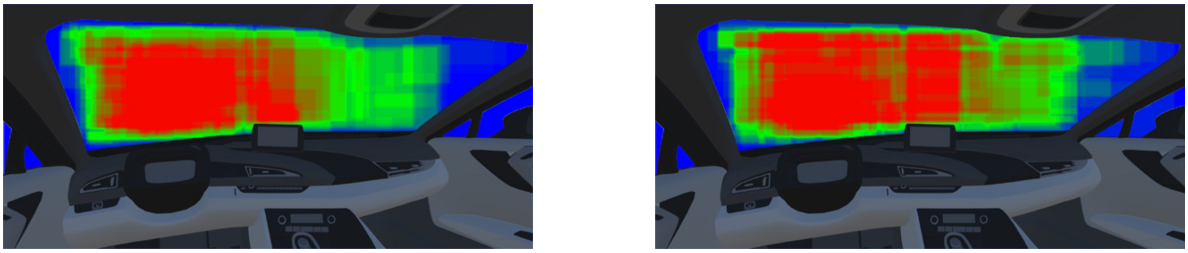
(j) Heatmap displaying social media windows (**S**) according to female drivers.

Figure 12: Level 5 heatmaps displaying the WSD preferences for male (left) and female (right) drivers.



(a) Level 3 heatmap generated from drivers' preferences in the city scene.

(b) Level 3 heatmap generated from drivers' preferences in the highway scene.



(c) Level 5 heatmap generated from drivers' preferences in the city scene.

(d) Level 5 heatmap generated from drivers' preferences in the highway scene.

Figure 13: Heatmaps for level 3 (top) and level 5 (bottom) automation; differentiated by city (left) vs. highway (right) environment.

is highly preferred as opposed to a static one where each space on the WSD is assigned a content type. An example is a large "main" window in the driver's field of view, surrounded by smaller "notification" windows. The content the driver focuses on would be displayed in the main window, and as notifications (e. g., incoming email) arrive, the driver can swap content types. Few participants mentioned that they would like to utilize the side window in addition to the windshield for customizable content. Another interesting aspect is comfort. Participants strongly preferred to place content on the driver side, in order not having to rotate or tilt the head to see the content. Additionally, for the level 3 scenario, participants stated that content displayed on the passenger side would be too distracting. Furthermore, windows utilized in portrait mode were strongly associated with lists, such as song, email, or to-do lists. Detailed content, however, such as a concrete email, should be visualized in landscape mode.

4.8.2 Interaction Management

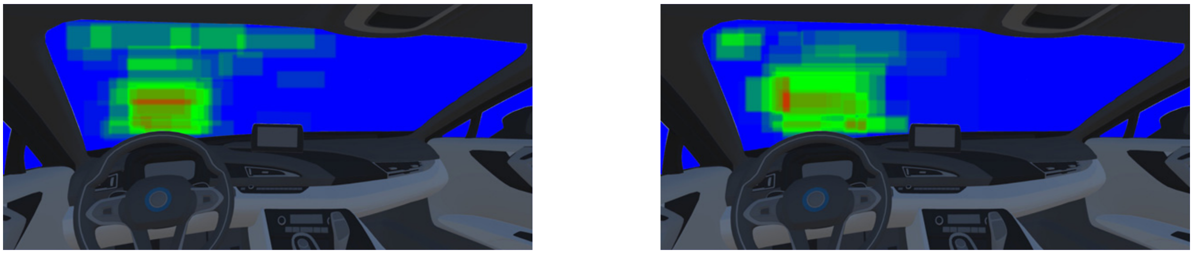
We also asked participants wondered, how they could imagine to interact with the WSD. The most common answer was **gestural interaction**. For example, one could perform a swipe gesture to change window contents or dismiss notifications appearing on the WSD. Another answer was interaction using **voice commands**. Since gaining more and more popularity in home automation systems, natural language processors could be a potential interaction concept in highly automated vehicles. Further answers included already existing hardware interfaces, such as rotary knobs and buttons/switches on the steering wheel.

4.8.3 Trust in Automated Driving

We recognized that most participants, being informed that they cannot take over the vehicle in level 5 driving, still placed warning windows on the WSD. When asked about this oddity, the vast majority of them stated that they wanted to know "what the system thinks", "be kept up to date with the driving situation", and therefore being able to prepare should a dangerous circumstance arise. This is consistent with state of the art in trust research on highly automated vehicles [35]. Those who did not place warning windows, stated that they would only drive in a fully automated vehicle if it is completely safe and they can trust it completely, thereby rendering warnings needless.

4.8.4 Privacy

An obvious issue that arises with large displays is privacy [11, 29]. Many participants stated that they would not want



(a) Heatmap displaying warning windows (**W**) in the city scene.

(b) Heatmap displaying warning windows (**W**) in the highway scene.

(c) Heatmap displaying vehicle-related windows (**V**) in the city scene.

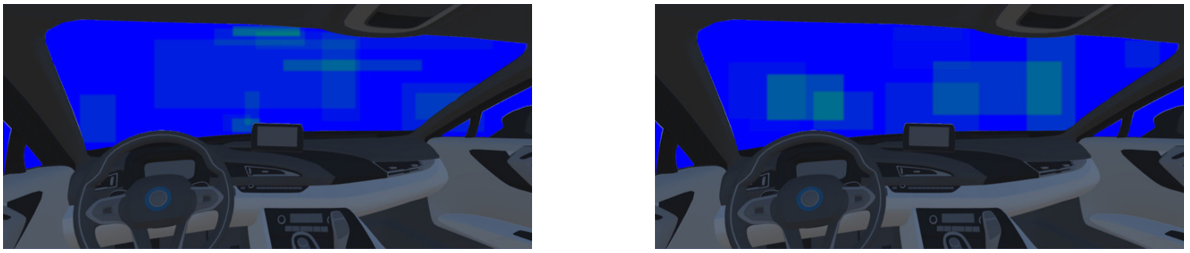
(d) Heatmap displaying vehicle-related windows (**V**) in the highway scene.

(e) Heatmap displaying work-related windows (**O**) in the city scene.

(f) Heatmap displaying work-related windows (**O**) in the highway scene.

(g) Heatmap displaying entertainment windows (**E**) in the city scene.

(h) Heatmap displaying entertainment windows (**E**) in the highway scene.



(i) Heatmap displaying social media windows (**S**) in the city scene.

(j) Heatmap displaying social media windows (**S**) in the highway scene.

Figure 14: Level 3 heatmaps displaying the WSD preferences for the city (left) and highway (right) scene.

(a) Heatmap displaying warning windows (**W**) in the city scene.

(b) Heatmap displaying warning windows (**W**) in the highway scene.

(c) Heatmap displaying vehicle-related windows (**V**) in the city scene.

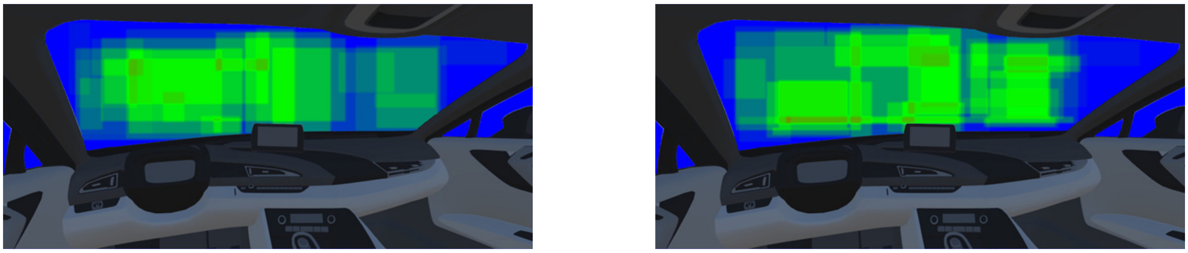
(d) Heatmap displaying vehicle-related windows (**V**) in the highway scene.

(e) Heatmap displaying work-related windows (**O**) in the city scene.

(f) Heatmap displaying work-related windows (**O**) in the highway scene.

(g) Heatmap displaying entertainment windows (**E**) in the city scene.

(h) Heatmap displaying entertainment windows (**E**) in the highway scene.



(i) Heatmap displaying social media windows (**S**) in the city scene.

(j) Heatmap displaying social media windows (**S**) in the highway scene.

Figure 15: Level 5 heatmaps displaying the WSD preferences for the city (left) and highway (right) scene.

to share sensitive and/or personal information with other vehicle passengers. While participants noted that for some content types privacy may not be an issue (e. g., watching a movie), work-related or social media content would be preferred to "invisible" to other passengers.

4.8.5 Context Awareness

It was further noted by some participants, when asked why they placed non-warning windows in the driver's field of view in level 3 driving, that they expect all windows to disappear when a dangerous situation occurs that would require the attention of the driver, and a large warning window should pop up notifying the driver what to do. Additionally, some participants stressed that on a work day, they would like to have work-related content on the WSD, while on weekends, entertainment and social media content are favored. For daily commutes, few participants added that they would like to see entertainment content, especially, when stuck in a traffic jam. Context aware systems could include users' daily routines and adapt WSD contents according to their preferences.

4.9 Survey Responses

In a post questionnaire we asked the participants general questions relevant for the use of AR-WSDs in vehicles. Participants had to rate their agreement on a 7-point Likert scale (7 = fully agree, 4 = neutral, 1 = fully disagree, see Figure 16). The results reveal some interesting insights. The majority of our experiments were students and staff of a technical university, a circumstance which is reflected in the answers. The majority considers themselves as tech-savvy (*Mdn* = 6). They stated that they would use automated vehicle technology extensively if available (*Mdn* = 5), what indicates a relatively high acceptance among study participants (compared to other surveys, such as [13] or [27]). Only few can imagine to wear AR glasses while driving (*Mdn* = 3) to get additional information overlays, suggesting that complex AR concepts cannot be implemented until sophisticated WSDs are available. An interesting economical possibility may emerge for mobility/transport providers [3]. Few respondents (*Mdn* = 2) stated to allow advertisements on WSDs if this would reduce or even omit the costs of individual mobility. However, the younger participants were strongly in favor of displaying ads for the benefit of cheaper mobility (*Mdn* = 5). Additionally, many participants (*Mdn* = 5) can imagine a WSD to become the only display in a vehicle. To our surprise, elderly participants were more likely to accept WSDs as only in-vehicle display (*Mdn* = 6), while younger drivers stated they would still have demand for center consoles or other display locations (*Mdn* = 4).

5 Discussion

Considering the individual research questions, WSDs are an interesting concept in combination with automated vehicles. Our results show that potential users might use them extensively (**RQ1**). Drivers prefer WSDs to display data from various information sources, and thereby consider the safety-related limitations of different levels of automation. In conditional automation (level 3), it is important for most drivers to be able to see what is in front of the vehicle, and thus they did not utilize content in their direct line of sight. Furthermore, drivers emphasized vehicle-related data such as warnings or dashboards, and rated them as very important. In fully automated driving

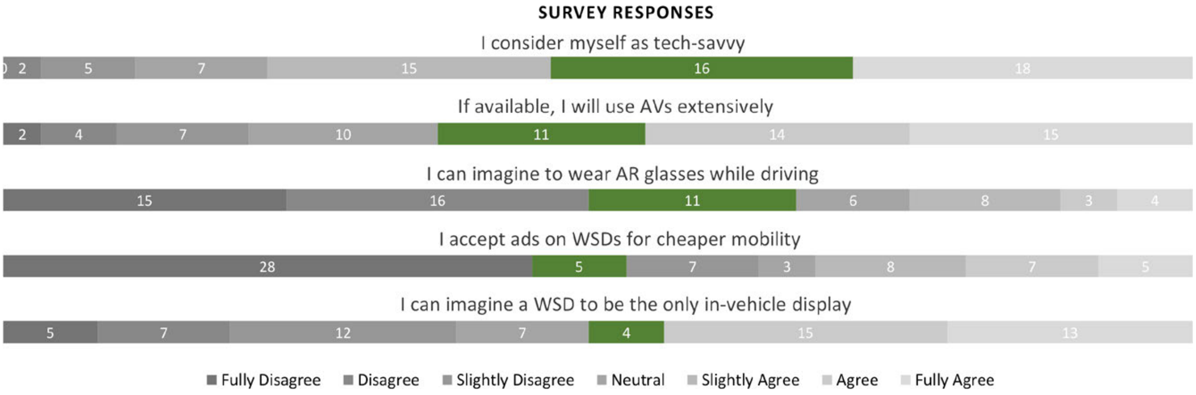


Figure 16: Likert plots showing the results of the survey questions conducted after the experiment. The medians are highlighted in green.

however, they shifted their preference more to non-driving related tasks and used much larger areas for entertainment, work or social media related applications (**RQ2**). Although users nowadays are familiar with portrait formats (such as used by many smartphone applications), most windows were characterized with a landscape format (**RQ3**). Regarding **RQ4**, there is some general agreement on the locations of vehicle-related information or warnings, that could partly emerge from their existing driving experiences (i. e., vehicle dashboards located directly above the steering wheel). Additionally, the center perspective was commonly used in fully automated driving to engage in non-vehicle related activities, such as media consumption or work activities. Answering **RQ5**, drivers wanted warning windows to be the least transparent in both automation scenarios. In level 5, however, content associated with work, entertainment and social media was drawn with less transparency than in level 3, in order to focus more on these tasks as opposed to the outside environment. In both conditional and full automation, warnings and vehicle-related dashboards were perceived as the most important content types. In full automation, however, work-, entertainment- and social media-related content gain (relative) importance (**RQ6**). When grouping our participants by age and gender, we also found interesting differences. Male participants strongly favored content in the driver's field of view in conditional vehicle automation, and they used more windows, while female drivers preferred to observe the outside environment and therefore placed content windows in the peripheral areas of the WSD. In full automation, both male and female drivers utilized the entire WSD. Generally, women used less transparency for their content windows (**RQ7**). When considering age, elderly drivers tend to place fewer content windows on the WSD, and made them smaller and more opaque than their young counterparts (**RQ8**). The driving environment, which we separated into urban (city) and highway, also had some influence on participants' WSD preferences. Especially work-related content windows were more commonly utilized in the city scene. Additionally, drivers generally preferred less transparent windows in the city scene (**RQ9**).

6 Conclusion

In this work we have evaluated user preferences for windshield displays by allowing participants of a lab study ($N = 63$) to freely choose position, size, transparency and importance of different content windows. We have further investigated the impact of different levels of automation (L3: conditional automation, and L5: full automation). Our results indicate the most important and most prominently used areas of windshield displays as desired by potential users, as well as the use of different content types (such as vehicle-related information, warnings, or entertainment) with respect to the level of automation. Drivers seem to be well aware of the implications of different autonomy levels and vehicle capabilities. For example, in level 3 driving, where drivers need to quickly assume vehicle control in case of take-over situations, warnings or vehicle-related information received higher importance and were used most often, while content relevant for non-driving related tasks was placed in comparably small windows in more peripheral areas of the WSD, thereby avoiding occlusion of the outside environment. In contrast, in fully automated driving, entertainment, work-related, or social media content received more importance and commonly span over large areas of the windshield display. Additionally, we highlighted differences in user preferences according to age, gender and the environment. Our results show that designers should take our findings regarding the use of different content types and their position, size, transparency and priority on the WSD into consideration when designing WSD applications.

6.1 Limitations

We are aware that our setting has some limitations. First, it was designed as lab experiment in a static environment. Preferences might slightly differ if a real driving scene would show participants that some areas used for displaying information could occlude important parts of the surrounding environment (and not only the center perspective, i. e., pedestrians entering a crosswalk from the left, passing cyclists from the right at a crossing). While the static user study setup appears technically simple, it provides us with essential and initial information about the basic usage of windshield displays for a multitude of different drivers. Further, we did not include any kind of view or interaction management – if users could switch applications, the chance could increase that similar content types (such as videos, office, or web applications) are displayed within the same window.

Another limitation that needs to be addressed is the extent at which WSDs would be used in a real-world scenario. Many people have smartphones and wearables such as smartwatches. When they are presented with automated vehicles and WSDs, how likely will they transition content, and what specific content, from their personal devices to either private shielded or semi-public WSDs? While we specifically told participants to imagine being alone in the vehicle, with no other passengers, the issue of shared vehicles (e. g., public transport) was not addressed in this research.

6.2 Future Work

In future studies we also want to investigate the shape of content windows. Although TVs, smartphones and computer monitors usually display their content in a rectangular shape, WSDs could differ. [5].

Large displays, especially when used in a public context, would also raise some privacy concerns, both in-vehicle and outside [1], that should be addressed in the future. We further want to use the collected heatmap data, i. e., the core content area to show concrete information such as media playlists or a video conference in order to allow the drivers to interact with the WSD application, and investigate the visual complexity of WSD applications in general, regarding multiple factors (such as layout, color coding, typography, etc. – similarly as Riegler et al. did in the mobile domain [21], [22]), including eye trackers. Another important aspect for investigation is, if changing environments and scene complexity (i. e., traffic jams, commuting) as well as the travel purpose (i. e., business vs leisure trip) would have an impact on user preferences. Finally, we want to conduct a driving simulator study to find out how participants react to content presented on WSDs during (simulated) drives. For such a dynamic scenario, we will use the gathered data from this study as default values and we will further investigate how drivers would or would not alter them in these varying context situations.

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