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Communicating minimal risk maneuvers to passengers in highly automated vehicles: Ensuring hedonic user experience with media rich in-vehicle HMIs

Thorben Brandt *, Marc Wilbrink, Michael Oehl

German Aerospace Center (DLR), Germany

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ABSTRACT

With the introduction of highly automated vehicles (HAV; SAE Level 4) driverless mobility systems may fundamentally change public transportation. For potential passengers of these systems, new situations may arise, leaving them without a driver to directly communicate with. This can be problematic when the driving automation is confronted with situations it might be unable to manage by itself, which would cause a minimal risk maneuver (MRM), e.g. a complete standstill of the vehicle. Some concepts enhance these systems with a remote assistant who can support the HAV, adding novelty to the transportation process. This increased novelty may result in user discomfort for passengers, causing a need for information systems that address this. One possibility to do so and to thus improve hedonic quality and thus comfort for passengers is by providing system transparency via a media rich in-vehicle Human-Machine Interface (iHMI), which provides information to passengers about the ADS and its processes. However, there is still a gap in research on the ideal communication mechanism to ensure good hedonic quality and comfort during these situations. We conducted a simulator study in virtual reality (VR), investigating interfaces based on media richness theory to address this issue. The interface provided a multi-layered iHMI consisting of transparency information presented with varying levels of media richness. In a block design, participants experienced three versions of an iHMI, one presenting information via text, another combining text and auditive presentation and a third adding a human avatar simulating Face-to-Face communication. After each scenario, participants completed questionnaires regarding understanding, predictability, trust and user experience. Study results reveal significant increases in the hedonic quality of user experience and trust towards the system for interfaces with increased media richness, providing a first step towards enhancing user comfort with iHMI in automated mobility systems during challenging situations for the automation system, such as MRM.

1. Introduction

Since German legislation allows the introduction of (highly) automated driving systems (ADS, SAE Level 4, Society of Automotive Engineers, 2021) into real traffic (Haupt, 2022), the implementation of driverless vehicles in public transportation has become realistic. While these driverless vehicles offer many benefits, like safety and efficiency, they remain challenging (Chan, 2017). One of these challenges is caused by replacing the driver with the ADS, leaving a gap in information transfer to passengers that needs addressing (Huff Jr et al., 2021; Meurer et al., 2020). In manually driven vehicles, a driver is present to provide information on the situation, delays or other problems in the transportation process. With ADS, this human driver no longer provides information or reassurance to passengers. This may discomfort passengers of these vehicles, as they are now confronted with the same issues and potentially more than they would be in manual vehicles, without a human driver to reassure them and provide information if necessary (Wiegand et al., 2020).

ADS utilize artificial intelligence (AI) to execute the driving related tasks, e.g. object detection or path planning (Mishra et al., 2022; Rao and Frtunikj, 2018). Because the AI's abilities are limited, the abilities of the ADS are limited as well (Kang et al., 2022; Karakaya et al., 2020). Current design guidelines (Haupt, 2022) of ADS require them to execute a minimal risk maneuver (MRM), e.g. where the vehicle may stop, when it encounters a limit in its design domain. To support the driving system in these cases, a remote assistant can function as a fallback (Kettwich

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* Corresponding author. Lilienthalplatz 7, 38106, Braunschweig, Germany.
E-mail addresses: thorben.brandt@dlr.de (T. Brandt), Marc.Wilbrink@dlr.de (M. Wilbrink), Michael.Oehl@dlr.de (M. Oehl).

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et al., 2021). A remote assistant can support the ADS from a distance by giving instructions to the ADS that help solve the issue at hand. This requires the assistant to quickly assess situations, understand the issue and provide solutions (Kettwich et al., 2021; Schrank et al., 2024). The assistant's task does not include providing information to passengers about the system and its process. This leaves a gap in passengers' ability to understand the situation potentially leading to user discomfort. This informational gap can be addressed by the In-Vehicle Human-Machine Interface (iHMI). But addressing this gap, causing user discomfort, requires new approaches in iHMI design. To close the gap transparent information about the situation can improve passenger's understanding of the current MRM and how it is resolved and hence improve their understanding and user comfort (Nordhoff et al., 2020; Oliveira et al., 2020). This leads to a lot of information about the ADS in the iHMI that the design should account for (Brandt et al., 2024). A way to do so might be Media Richness Theory.

1.1. Media richness theory

Media Richness Theory (MRT) assumes that every communication medium has a certain "richness" to itself, with direct communication (i.e. Face-to-Face) having the most richness (Daft and Lengel, 1986; Suh, 1999; Valacich et al., 1994). Richness describes the ability of a medium to communicate information with a certain clarity (Daft and Lengel, 1986). Research also suggests that other factors, like subjective experience and individual concepts also influences perceived richness (Hornung, 2015; Ishii et al., 2019). Certain media add spatial information beyond the essence of what is being communicated further increasing their richness (Daft and Lengel, 1986). Therefore, the medium itself adds value to the communication without adding to information richness. Complex information is ideally communicated using a rich medium, and simple information using a leaner medium (Lo and Lie, 2008; Vala et al., 2022). So, in order to account for the informational gap in the vehicle's communication, a medium with suitable richness in the iHMI is needed.

What passengers might also miss is the ability to communicate or interact with a driver (Oliver, 2019). Interactive communication is perceived as richer than unidirectional communication (H.-L. Yang and Lin, 2019). Additionally, some theories assume that a medium's richness is also determined by its ability to communicate synchronously (Dennis et al., 1998). So, rich media can transport lots of information quickly, synchronously and interactable. For example, transparent interfaces that provide information about MRMs and their resolution process, described by Brandt et al. (2024) provide a lot of information to passengers. Communicating these amounts of information might benefit from this increase in media richness.

1.2. Trust and understanding by media rich communication

Originally, MRT investigated the influence of media richness in information communication for task communication (Suh, 1999). Resulting from this efficient communication of complex information rich media support the understandability of the information in interfaces as well (Vala et al., 2022). Depending on task and desired experience for the recipient, different media would be more or less feasible (Carmichael et al., 2021; Suh, 1999). A goal of using the adequate medium for communication would be an improved understandability of the information (Vala et al., 2022). A result of this understanding is an adequate mental model or representation of the communicated concept (Carroll and Olson, 1987). Mental models are the result of continuous processes of learning and experiencing, e.g., by interaction with an object (Beggiato and Krems, 2013). This interaction is influenced by the quality or clarity of the communicated information, e.g., through the system's iHMI (Durso et al., 2016). In addition to improving the efficiency of communication, rich media might also improve user experience. Since passengers of a highly automated vehicle (HAV) that utilizes ADS, are primarily passive users, it is more important to provide good user experience than actual understanding and predictability. Though understanding and predictability is beneficial (Detjen et al., 2021), subjective perception predicts actual user behavior better (Schneider et al., 2023). Using rich media improves accessibility and transparency of the information communicated and thus increases passenger's user experience (Ehsan et al., 2021). This may improve passenger's user comfort as a result and promote trust development as well.

Trust is an important factor in terms of positive user experience and user comfort (X. J. Yang et al., 2017; Yuen et al., 2021). It results from better understandability as it enables users to know when to trust the system based on its functioning or abilities (Hoff and Bashir, 2015). When a system is more understandable, e.g. because it presents relevant information about its activity, it provides users with the ability to identify errors in the system, thus acquiring knowledge about the trustworthiness of the system (Desai et al., 2012; Hoff and Bashir, 2015). Since users have a tendency to choose media that can transport more information when they are faced with a new communication partner over longer distances (Lo and Lie, 2008). The reason for this could be a better experience when using richer media that are more capable of communicating higher amounts of information that are needed to evaluate the trustworthiness of the communication partner. Additionally, social aspects also positively influence trust of users (Oliver, 2019). In customers of computer products, multimodality has shown to improve trust as well (Mohamad, 2020). Since, richer media can also provide more social cues, they provide more information to evaluate a communication partner's trustworthiness (Hornung, 2015).

Automated vehicles lack information provided to passengers because no driver is available to provide additional information. This can leave passengers in discomforted situations requiring different iHMI than manual vehicles (Meurer et al., 2020). Richer media, like Face-to-Face communication, can provide more, especially socially relevant, information like a driver would (Rockmann and Northcraft, 2008). Therefore, richer media may be more suitable for communication in iHMI to provide system transparency information during MRM resolution. Media richness can be utilized in iHMI by adding modalities, like sound and video ideally surrogating Face-to-Face communication. An implementation that does this and addresses both modalities, are avatars that can enhance user comfort (Weitz et al., 2019). To investigate user comfort, we investigated several concepts we believe contribute to aspects of user comfort; *trust*, *user experience* and *understanding and predictability* (Peng et al., 2024). We therefore investigated the **research question**: "*Does media richness improve passengers' understanding and predictability and user experience of automated driving systems (ADS) when information is communicated via an internal Human-Machine Interface (iHMI) during minimal risk maneuvers (MRMs) in a highly automated vehicle (HAV)?*"

1.3. Hypothesis

Following the proposed argumentation, using richer media for communication leads to a better understandability of the communicated information. This results in a better passenger understanding and predictability of the ADS and the MRM resolution process, leading to the first hypothesis:

H1. "*Higher levels of media richness presented by an iHMI in an HAV communicating information about an MRM resolution to its user leads to increasing passenger understanding and predictability.*"

As a result of this improvement of understanding and predictability, passengers are more capable to estimate the system's capabilities and thus, when and how to trust it. In addition, social cues resulting from rich media (e.g. Face-to-Face communication) could improve perceived trustworthiness of the system as well. Socially "available" systems can provide a better sense of social support and interactivity for passengers, thus, increasing trust. These considerations lead to the second hypothesis:

H2. "*Higher levels of media richness in communication used by an iHMI in an HAV communicating information about the resolution process of MRM to its passengers lead to higher passenger trust.*"

Improvements in understandability of information in an iHMI results better acquisition of the information resulting in a better pragmatic quality of user experience. Previous research also suggests that users prefer interacting with a media rich interface (Carmichael et al., 2021; Valacich et al., 1994). This preference results in higher evaluations of the hedonic quality of user experience leading to the third hypothesis:

H3. "*Passengers of an HAV perceive higher user experience of an iHMI when the iHMI is presenting the information about the MRM resolution process using richer media.*"

The aim of these hypotheses is to provide insights in the informational design requirements of an iHMI during MRMs. Without information passengers have no insight into the ADS itself and the resolution process including remote assistance. To maintain user comfort solutions to the informational design in an iHMI are needed.

2. Materials and methods

The following chapter describes the used method, materials, and research design.

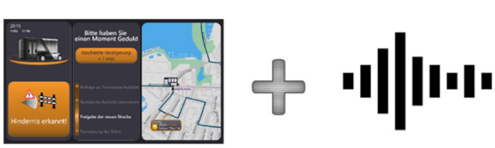
2.1. Sample

The sample consisted of 29 participants (21 = male, 8 = female) with an average age of M = 44.55 years (*SD* = 19.92). Participants were asked about their attitude towards automation using a single item ("*I think automation is […]*"; ([1] = "very good" to [5] = "very bad"). Participants reported a positive attitude towards vehicle automation (*M* = 1.97; *SD* = 0.67). All participants had a valid driver's license and spoke German (C1 level). Participants were recruited using a panel and social media posts on LinkedIn. They were incentivized with 20,- Euro.

2.2. Study design

In an experimental within study design, participants experienced three variants of an iHMI utilizing different levels of media richness (Table 1). In the "*Text*" condition, the iHMI provided information about the MRM and its resolution process via text (Brandt et al., 2024). In the "*Text* + *Audio*" condition, the communication was enriched by additional announcements that provided the same information via audio. In the "*Text* + *Audio* + *Avatar*" condition, the communication was enriched with an avatar representing Face-to-Face communication. The avatar provided the same information as the auditive announcements and was shown on the same screen as the text-based interface. The MRM resolution process was depicted in four steps, resulting in four auditive announcements or avatar appearances in each scenario.

Table 1
The three variants presented to participants with their respective modalities.

iHMI variants	Stimulus material
Text	
Text + *Audio*	
Text + *Audio* + *Avatar*	

Participants experienced a journey in virtual reality (VR) created with the Unreal Engine 5 (UE5; Epic GamesInc., 2022). The simulation was presented via a head-mounted-display (Varjo XR3 glasses) in a seated position. Participants had no controller to interact with the digital environment. They were able to talk to a researcher during the entire experiment. Each iHMI condition was shown in a block with three different traffic scenarios where the HAV performed an MRM with varying causes (i.e., due to a blocked road either by a truck, a construction site, or a puddle in the road). In every scenarios of the same block, the iHMI displayed the same condition. The presentation of the scenarios as well as the conditions was in randomized order, so that each interface variant was shown three times in a row. After each block, participants answered questionnaires about their experiences before they went on to the next iHMI condition.

2.3. Used iHMI variants

The variations in media richness were created by adding modalities to the communication to increase the iHMI's richness. In the "*Text*" interface, information like the vehicle status and stops were shown on the left side of the interface via text. Map-based route information appeared on the center and right side of the interface (Fig. 1). The amount of information depicted during MRM resolution in the interface was designed based on the interface proposed by Brandt et al. (2024). In case the vehicle performed an MRM, the depictions on the interface changed to the MRM-interface, providing additional information on the MRM resolution process including the remote assistant. In the MRM interface, the map view was reduced to provide additional space for more information. On the left side, vehicle status as well as a reason for the MRM were shown. Participants were not able to interact with the interface in any way.

In the "*Text* + *Audio*" interface an auditive announcement was added to the text condition. It provided the same information, only increasing media richness. For the "*Text* + *Audio* + *Avatar*" iHMI, an avatar was added to the "*Text* + *Audio*" condition but instead of just audio, the avatar presented the announcements replacing the text information with the avatar's appearance for the duration of the announcements (8–10 s.). The avatar surrogated Face-to-Face communication with the highest amount of media richness. The avatar was designed using the UE5 Meta Humans application (Epic GamesInc., 2022). The avatars appearance was evaluated in a pre-study (N = 59) comparing different avatar designs, in order to appeal to a large set of people and look as realistic as possible (Fig. 2).

2.4. Questionnaires

To evaluate the effect of media richness on measures for participants' user comfort, i.e., understanding, predictability, trust, and user experiences, subjective questionnaires were used. To measure user experience, the standardized UEQ-S (Schrepp et al., 2017) was used. To measure subjective trust, understanding and predictability the standardized *Trust in Automation* (TiA) Questionnaire by Körber and Gleissl (2022) was used. Additionally, a set of questions regarding the intention to use the shown ADS, and the need to interact with the remote operator was used to measure user preferences on a 7 point scale (1 = "Don't agree at all",

Fig. 1. Left: Interface design for the iHMI in the Vehicle without MRM. Right: Interface design for the *"Text" and "Text + Audio"* iHMI during MRM in the Vehicle.

Fig. 2. Avatar design for the "*Text* + *Audio* + *Avatar*" iHMI in the Vehicle during MRM (when the Avatar was speaking).

7 = "Totally Agree", Appendix A).

2.5. *Procedure*

Participants arrived at the research center where they were picked up by a researcher. They were brought to the VR-lab where they were instructed about the procedure, the VR simulation, and their rights according to the Declaration of Helsinki and had to consent to participate and to the data acquisition via form in accordance to the German data protection law (The World Medical Association, Inc., 2008). An ethics board also approved of the described study procedure. The participants then took part in their simulated ride through the city of Brunswick, where they experienced the different iHMI variants in different scenarios. After each trial they answered the questionnaires regarding trust, user experience and the after-trial questions. Participants were able to take breaks at any time. After experiencing all three iHMI variants in all three scenarios and answering the questionnaires, participants were finished with the experimental parts of the study. They were then brought back to the entrance of the research center.

Intra-subject effects were then calculated using an ANOVA for repeated measures to evaluate the TiA Questionnaire, the Understanding and Predictability Subscale, and the UEQ-S, with Bonferroni adjusted post-hoc tests. Sphericity was checked using Mauchly's test for sphericity ($p = < 0.01$) and results corrected accordingly, using Greenhouse-Geisser adjustment (Field, 2018). According to Shapiro-Wilk Test, none of the groups showed normal distribution, which was not adjusted for, since RM-ANOVA are resilient to violations (Berkovits et al., 2000). Effect sizes were calculated as Omega square to utilize a conservative measure ($\ddot{\omega}^2$; Small effect = 0.01, Medium effect = 0.06, Large effect = 0.14; Lakens, 2013).

3. Results

3.1. *Results regarding understanding and predictability*

In hypothesis one (H1), the influence of the iHMI's media richness on passengers' understanding and predictability of the automation was investigated. Results of the "understanding and predictability" subscale of the TiA showed values between M = 2.98 (SD = 0.35) for "Text" condition and $M = 3.22$ ($SD = 0.34$) for the "*Text* + *Audio*" condition (Table 2).

An ANOVA for repeated measures with a Greenhouse-Geisser correction revealed significant differences with a medium effect size regarding understanding and predictability between the variants (F (2.00, 56.00) = 3.59, $p = .034$, $\ddot{\omega}^2 = 0.08$). When using the Bonferroni-

Table 2
Results of Trust in Automation Subscale "Understanding and Predictability" regarding understanding of participants as a result of interaction with the iHMI variants.

Trust			95 %-CI	
	M	SD	Lower	Upper
Text	2.98	0.35	2.85	3.11
Text + Audio	3.22	0.34	3.07	3.37
Text + Audio + Avatar	3.1	0.41	2.94	3.26

adjusted post-hoc analysis, no significant effects on understanding and predictability in any of the conditions could be found. As a result, hypothesis one is not supported by the results and cannot be confirmed.

M = Mean, SD = Standard Deviation, 95 %-CI = Confidence Interval.

3.2. Results regarding trust

In hypothesis two (H2), the influence of the iHMI's media richness on passengers' trust was investigated. Descriptive statistics reveal almost no differences in mean (M) values for passengers' trust with varying media richness. This lack of variance also applies to the values for standard deviation (*SD*) (Table 3). Results range between $M = 3.31$ ($SD = 0.33$) for "*Text*" media richness and $M = 3.45$ ($SD = 0.33$) for "*Text + Audio*" media richness.

However, an ANOVA for repeated measures with a Greenhouse-Geisser correction revealed significant differences regarding trust between the variants for, $F(1.93, 54.05) = 4.13$, $p = .023$, $\ddot{\omega}^2 = 0.1$. Using a Bonferroni-adjusted post-hoc analysis, only the differences between "*Text*" and "*Text + Audio*" showed significant differences ($p = .032$; $M_{Diff} = 0.136$, 95 %-Confidence Interval [-0.263, −0.009]). Thus, the results did not completely support the hypothesis that media richness may influence passengers' trust towards HAV during MRM resolution, yet an influence may be possible.

3.3. Results regarding user experience

The UEQ-S questionnaire was analysed for hedonic and pragmatic subscales separately. The pragmatic subscale can be understood as the quality of task related aspects and the hedonic subscale as non-task related aspects like appeal and novelty.

3.3.1. Results in the pragmatic subscale of user experience

In hypothesis three (H3), the influence of the iHMI's media richness on passengers' perceived pragmatic quality was investigated. Participants reported mean values between $M = 5.44$ ($SD = 1.154$) for the "*Text*" only interface and $M = 5.83$ ($SD = 0.759$) for the "*Text + Audio*" interface in the pragmatic subscale of the UEQ-S (Table 4). An ANOVA for repeated measures with a Greenhouse-Geisser correction revealed no significant differences regarding pragmatic quality between the variants, $F(1.99, 55.85) = 1.65$, $p = .20$, $\ddot{\omega}^2 = 0.02$. Bonferroni-adjusted post-hoc analysis revealed no significant differences as well. The results do not support the hypothesis that different media richness influences pragmatic quality of an iHMI in HAVs during these MRMs.

3.3.2. Results in the hedonic subscale of user experience

In hypothesis three (H3) the influence of the iHMI's media richness on passengers' user experience using the hedonic quality subscale of the UEQ-S was investigated. Participants reported mean values between $M = 4.25$ ($SD = 1.8$) for the "*Text*" only interface and $M = 5.31$ ($SD = 1.17$) for the "*Text + Audio + Avatar*" interface in the hedonic subscale of the UEQ-S (Table 5).

An ANOVA for repeated measures with a Greenhouse-Geisser correction revealed significant differences regarding hedonic quality between the variants, $F(1.56, 43.68) = 14.40$, $p < .001$, $\ddot{\omega}^2 = 0.31$. A Bonferroni-adjusted post-hoc analysis revealed significant differences between "*Text*" and "*Text + Audio*" ($p = .005$; $M_{Diff} = -0.612$, 95 %-Confidence Interval [−1.057, −0.167]), "*Text*" and "*Text + Audio + Avatar*" ($p = .001$; $M_{Diff} = -1.060$, 95 %-Confidence Interval [−1.685, −0.436]), and "*Text + Audio*" and "*Text + Audio + Avatar*" ($p = .034$; $M_{Diff} = -0.448$, 95 %-Confidence Interval [−0.869, −0.027]). Results suggest that there is a positive influence of media richness on user experience. The influence presents itself with a large sized effect ($\ddot{\omega}^2 = 0.31$) (Fig. 3).

Table 3
Results of Trust in Automation Questionnaire regarding all the iHMI variants.

Trust			95 %-CI	
	M	SD	Lower	Upper
Text	3.31	0.327	3.184	3.433
Text + Audio	3.45	0.326	3.320	3.569
Text + Audio + Avatar	3.41	0.365	3.269	3.547

M = Mean, SD = Standard Deviation, 95 %-CI = Confidence Interval.

Table 4
Results of Pragmatic Quality in Automation Questionnaire regarding the iHMI variants.

Pragmatic Quakity			95 %-CI	
	M	SD	Lower	Upper
Text	5.44	1.154	5.009	5.887
Text + Audio	5.83	0.759	5.547	6.125
Text + Audio + Avatar	5.52	1.282	5.038	6.014

M = Mean, SD = Standard Deviation, 95 %-CI = Confidence Interval.

Table 5
Results of Hedonic Quality in Automation Questionnaire regarding all the iHMI variants.

Hedonic Quality			95 %-CI	
	M	*SD*	*Lower*	*Upper*
Text	4.25	1.794	3.568	4.932
Text + Audio	4.86	1.397	4.330	5.394
Text + Audio + Avatar	5.31	1.173	4.864	5.757

M = Mean, SD = Standard Deviation, 95 %-CI = Confidence Interval.

3.4. Results post-trial questions

Results of the post-trial questions showed results between $M = 4.97$ ($SD = 1.54$) and $M = 5.59$ ($SD = 1.35$) on a scale from 1 ("Don't agree at all") to 7 ("totally agree") for "*If you had an important work appointment, how well informed would you feel by the vehicle interface?*" and $M = 4.86$ ($SD = 1.74$) and $M = 6.14$ ($SD = 1.03$) for "*How well did you feel informed by the vehicle's depictions?*".

An ANOVA for repeated measures with a Greenhouse-Geisser correction revealed significant differences regarding „ *If you had an important work appointment, how well informed would you feel by the vehicle interface?*", between the variants for, $F(1.81, 50.84) = 4.27$, $p = .022$, $\ddot{\omega}^2 = 0.1$. Using a Bonferroni-adjusted post-hoc analysis, only the differences between "*Text*" and "*Text + Audio*" showed significant differences ($p = .043$; $M_{Diff} = -0.586$, 95 %-Confidence Interval [−1.159, −0.014]).

An additional ANOVA for repeated measures with a Greenhouse-Geisser correction revealed significant differences regarding „ *How well did you feel informed by the vehicle's depictions?*" between all variants for, $F(1.95, 52.80) = 10.00$, $p < .001$, $\ddot{\omega}^2 = 0.24$. A Bonferroni-adjusted post-hoc analysis revealed significant differences between "*Text*" and "*Text + Audio*" ($p = .001$; $M_{Diff} = -1.214$, 95 %-Confidence Interval [−1.938, −0.491]) and "*Text*" and "*Text + Audio + Avatar*" ($p = .021$; $M_{Diff} = -0.857$, 95 %-Confidence Interval [−1.608, −0.106]). Results of the post-trial questions support hypothesis three that there is an influence of media richness on user experience (Fig. 4).

4. Discussion

The study investigated the influence of media richness on user comfort. Results indicate support for one of the three hypotheses.

4.1. Understanding and predictability

hypothesis one (H1) investigated the influence of media richness on passengers' understanding and predictability of the ADS. A repeated

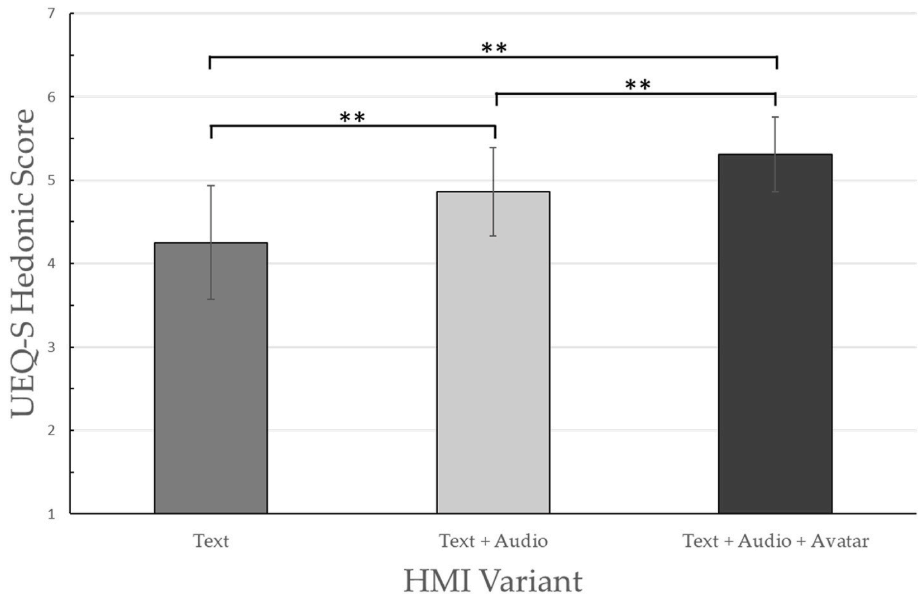


Fig. 3. Mean values for UEQ-S hedonic subscale with 95 %-CI and significant differences (* = p < .05, ** = p < .01).

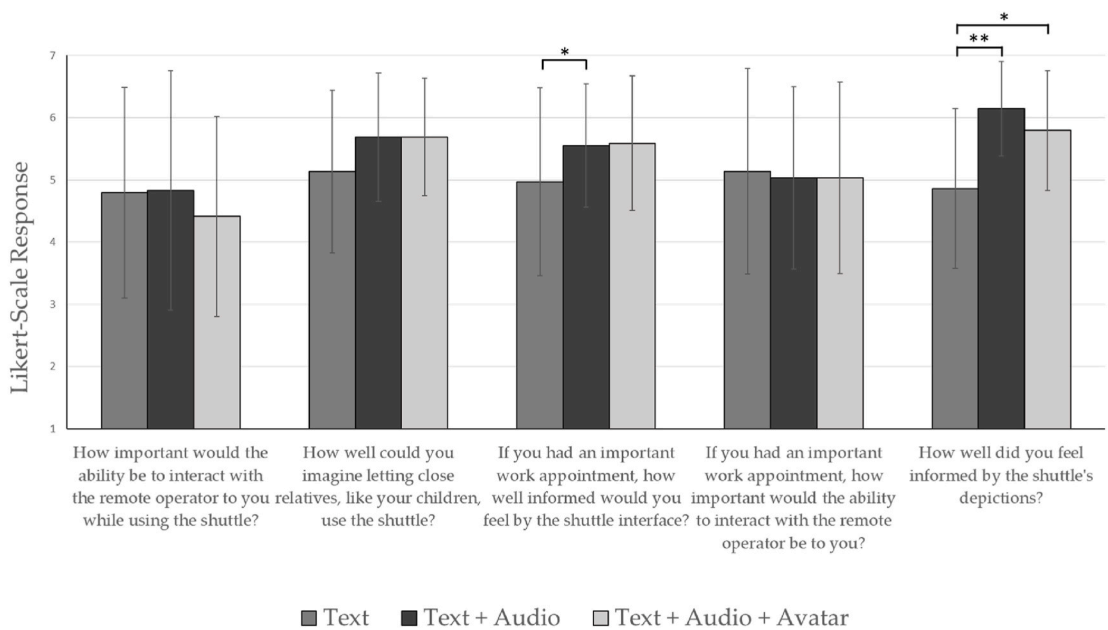


Fig. 4. Mean values with 95 %-CI regarding post-trial questions for each iHMI variant with significant differences (* = p < .05, ** = p < .01).

measures ANOVA for participant's understanding and predictability of the system was significant, but was not confirmed by results of the Bonferroni adjusted post-hoc tests. Therefore, the hypothesis is not supported by the results. In theory, explanation quality should increase with media richness (Vala et al., 2022), leading to a better understanding and predictability of the system because information can be acquired more easily and quickly (Hornung, 2015). Since, the scenarios in this study were relatively simple they might not have required more information for participants. Communication might only benefit from media richness in situations that actually require more information. No increases in understanding and predictability suggest that this was not the case and no additional media richness was needed due to the situation's simplicity.

Another possibility is that participants did not perceive the situations as very critical and had no desire to understand them or the systems behaviour. If participants did not experience discomfort, they might not develop a need for a better understanding of what is happening at the moment and what the ADS is going to do. In uncritical situations, where not much information is needed, lean media would suffice to provide enough richness for proper communication (Lo and Lie, 2008). User discomfort may not have been sufficient enough for participants to actually require reassurance or social presence (Oliver, 2019). The avatar which also provided richness in terms of the latter, would be unnecessary in that case. In more critical situations, the passengers' need for information may be different resulting in different requirements for media richness. We therefore conclude that there is no influence of media richness on passengers' understanding and predictability of the HAV, at least in the given situations.

4.2. Trust

hypothesis two (H2) investigated the influence of media richness on passengers' trust. In theory, rich media improves passengers' trust. Higher richness, inducing social presence can increase perceived competence and trustworthiness of the ADS (Rockmann and Northcraft, 2008). The results of the RM-ANOVA support this consideration. Subjective trust ratings where significantly improved with increasing richness providing evidence that media richness does influence passenger trust. But, post-hoc tests did not reveal a systematic effect on trust. The hypothesis is therefore not supported by the results. The "*Text + Audio*" condition did show higher trust scores than the "*Text*" condition. Yet, in the condition "*Text + Audio + Avatar*" results were not significantly higher than in the "*Text*" and "*Text + Audio"* interfaces indicating that the avatar as the richest medium, contrary to our hypothesis, did not add significantly to participants' trust. So, the effect found in the ANOVA cannot be generalized with the results of the present study. This lack of significance might be explained by differences in personal preference leading to increased volatility of passenger ratings (Kraus et al., 2015), which could counteract possible effects. Though some participants expressed opposing views on the avatar, there is no difference in variances in the results of the avatar condition to confirm this consideration.

Although the avatar might have added some sort of social presence, this may not have been perceived as appealing. The avatar design was not perfectly synchronous with the announcement which might have undermined its anthropomorphic qualities inducing uncanniness instead (Kulms and Kopp, 2019). Additionally, participants might have resented the avatar as artificial undermining its effect on social presence. But, questions regarding interaction preference with the remote operator showed no significant differences with results being the lowest in the avatar condition. This indicates that the avatar may have induced social presence after all, leading to a lower desire to talk to a real person. Therefore, hypothesis two (H2) is rejected and we conclude that media richness does not influence passenger trust in the HAV during MRM resolution.

For the variables, trust, understanding, and predictability, results suggest no benefit of the avatar in the given situations. Increasing media richness, as provided by the avatar, did not improve either trust nor understanding and predictability. This may indicate that the amount of media richness is not needed in relatively uncritical situations. In more critical situations that cause higher amounts of discomfort, the avatars may prove more useful towards certain aspects of user comfort, such as trust or understanding and predictability. Nevertheless, to provide a more precise sense of the usefulness of media richness, larger sample sizes might be required, as the current study provided a rather small sample. This relativises the insights into the real usefulness of the avatar as smaller effects may have remained undetected. Future research may also utilize a more homogeneous age range, as this study utilized a rather inhomogeneous sample.

4.3. User experience

Hypothesis three (H3) investigated the influence of media richness on user experience. The pragmatic quality of user experience of the interfaces did not improve with richer media in the RM-ANOVA. A reason for this could be that the interface with the avatar replaced the text interface. This handicapped the participants' ability to acquire the information via text while the avatar was shown, counteracting the interface's pragmatic quality. Evaluations regarding the pragmatic quality as well as participants' perceived understanding could be worse as a result. Though the avatar presented the same information that would have been available to participants in the text-based interface, and it provided an increase in richness, we cannot completely rule out that participants subjectively felt a decrease in quality of information communication.

However, the RM-ANOVA for the hedonic quality of the interface showed significant differences. These are supported by post-hoc analysis between each interface condition. The results therefore suggest a positive influence of media richness on the hedonic quality of passenger communication. Results indicate that the general appeal has been improved but the quality of the communication was not. Since media richness did not improve trust ratings, the avatar depiction might not have improved the perceived competence of the system as suspected. Instead, the depiction may have improved awareness for the new situation by providing a prominent change in the interface. This may have improved the perception of the interface as it may have appeared suddenly more exciting and appealing. What cannot be ruled out is if the avatar was perceived as uncanny. It was rated positively in the pre-study, but personal preference may have influenced participants' evaluation of the interface with the avatar, as it can vary greatly based on users' experience, self-image, and expectations (Jang et al., 2010; Yee and Bailenson, 2007). Accounting for this is increasingly difficult and was not done in the present study, as the aim was to evaluate the interface's media richness, not the avatars appeal. Additionally, participants were only confronted with a female avatar. This may have somewhat biased the evaluations as well, as identification with the avatar itself may not have been the same for each participant (Yee and Bailenson, 2007).

Results of the post-trial questions support the conclusion that media richness had a positive influence on user experience. Participants felt significantly better informed by the interface including the avatar than without any addition in media richness. Results showed a significant difference for the question „*If you had an important work appointment, how well informed would you feel by the vehicle interface?*", confirmed in post-hoc analysis for the announcement. This was also true for the question „*How well did you feel informed by the vehicle's depictions?*", which showed significant differences, confirmed in post-hoc tests for all conditions. Results therefore indicate a positive influence of media richness on user experience and user comfort. At least for multimodality of information communication as there were no significant differences between the avatar and the other conditions in any of the questions, indicating that the avatar did not add significant value to the information communication. We can still assume that the avatar provided a better experience overall, but not in terms of information communication. As discussed, this might have been caused by the avatar replacing the text information, counteracting positive effects. We conclude that there is an influence of media richness on user experience and thus partly accept hypothesis three.

5. Conclusions

The present study investigated the influence of media richness in iHMIs for HAVs on passengers' user comfort. It provides evidence that media richness positively influences passengers' hedonic quality of their user experience, especially during MRM resolution. This plays an important role, as the passengers' needs are also relevant for the workplace design for remote assistants (Aramrattana et al., 2024). Particularly during critical situations more information about the MRM resolution process, and even a direct connection to the remote assistant might be needed (Schrank et al., 2024). However, in terms of media richness, more might not always be necessary or better. While the ideal amount of media richness may depend on the circumstances, any amount of added richness might be enough to profoundly improve the hedonic quality of user experience, when compared to single modality interfaces. We assume that the lack of a human driver can be in part compensated with a media rich interface. Passengers' understanding, predictability and trust towards the ADS might be influenced primarily by the amount of information provided. A lack of important information regarding the ADS and MRM resolution process might not be compensable with just media richness. We therefore propose that interfaces are designed in an information and media rich way that enables passengers to understand and predict the ADS, the MRM resolution process, and provides improvements in user comfort, particularly in the hedonic quality of the interface, based on situational needs. What the definitive needs for media richness and information in iHMI are, may remain unknown until real world studies provide concrete results.

CRediT authorship contribution statement

Thorben Brandt: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marc Wilbrink:** Writing – review & editing, Visualization, Software, Resources. **Michael Oehl:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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