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Exploring road user uncertainty during encounters with automated vehicles: A repertory grid study

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ABSTRACT

Automated vehicles (AVs) are becoming reality, and their interactions with other road users (ORUs) can evoke human uncertainties, which could be addressed using external human-machine interfaces. This paper explores the perception of uncertainty from the perspective of ORUs interacting with an AV. Two scenarios of interactions with an AV were generated by the participants, and four pre-defined scenarios were shown with virtual reality. Using the Repertory Grid Technique, 25 participants compared these traffic scenarios to identify key factors influencing perceived uncertainty. Inductive qualitative content analysis of the factors identified by participants demonstrates that the environment, signaling, subjective evaluations, behavior and performance, and social dynamics influence uncertainty. We further assess the level of influence and uniqueness of these factors for interactions with AVs. Based on the findings, we discuss three key implications: (1) the diversity of factors and how addressing those requires a holistic approach, (2) the potential role of adaptations in the built environment and (3) the need for standardization to address uncertainties.

1. Introduction

When road users experience uncertainty, it can negatively influence their behavior. Human perceived uncertainty, referred to in this paper as uncertainty, can create fear or indecisiveness and can negatively influence the ability to process data to make a decision (Phillips-Wren and Adya, 2020). The link between uncertainty and emotions is predominantly directed towards negative emotional states, such as fear or anxiety (Morriss et al., 2022; Franssen et al., 2024). To reduce uncertainty, the brain searches for new information (Kramer, 1999, Keller et al., 2020).

Uncertainty experienced by other road users (ORUs) can be provoked when encountering automated vehicles (AVs) for numerous reasons. Automation that does not require control from a driver (i.e., SAE Level 4 and 5 (SAE International, 2021)), might have deviating driving styles compared to human drivers (Bellem et al., 2018, Bazilinskyy et al., 2021), and ORUs cannot rely anymore on explicit communication with a driver (such as gestures) (Sucha et al., 2017). To enable a better interaction between AVs and ORUs, research has focused on developing external Human-Machine Interfaces (eHMIs). These eHMIs could potentially be leveraged to reduce the uncertainty experienced by ORUs, since they could address the aforementioned search for more information when a human is experiencing uncertainty (Kramer, 1999; Keller et al., 2020). An eHMI can communicate in an egocentric way to tell the receiver what they need to do, or it can communicate allocentrically what the intent of the AV itself is (Bazilinskyy et al., 2019; Bauke Eisma et al., 2021). A literature review conducted in 2019 by Dey et al. (Dey et al., 2020) found 70 concepts of eHMIs. This same review demonstrates that most eHMIs are researched in the same typical setups, using typical pedestrian crossing scenarios, good weather and light conditions, and good road conditions. For this reason, it is important to develop and test eHMIs for other road scenarios as well. This raises the fundamental question of what situations even require the provision of additional information by an AV.

To better understand when other road users need additional information (from an eHMI) during encounters with an AV, this paper explores the dimensions that contribute to uncertainty. With ORUs, we mean vulnerable road users (such as pedestrians or cyclists) and drivers of manually driven vehicles. By focusing on ORUs instead of one particular type of road user, participants can compare differences between roles (similar to (Gao et al., 2024)) to generate a more holistic understanding of the factors that influence their perceived uncertainty.

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In the existing literature, the term uncertainty is often defined imprecisely or inconsistently (Anderson et al., 2019). To avoid further inconsistency, we establish a working definition of uncertainty for the purpose of this paper. Based on (Milliken, 1987; Grupe and Nitschke, 2013), this paper will define uncertainty as "an internal mental state resulting from the perceived inability to predict outcomes accurately". Using this definition, uncertainty comes close to unpredictability. However, the term uncertainty is used since it better captures the subjective aspects of a person's internal state (i.e., the experience) (Grupe and Nitschke, 2013). Concretely, this paper will focus on the following research question: *"What underlying factors influence the uncertainty of other road users during an encounter with an automated vehicle?"*.

To explore the dimensions of uncertainty, this paper will apply the Repertory Grid Technique (RGT). This technique was introduced by George Kelly in 1955 and is part of Personal Construct Psychology, which is a theory that describes that humans develop personal constructs about how they consider the world to work (Kelly, 1955). Although RGT was initially used in the setting of patient treatment, it has since been adopted as a method to externalize the personal views of individuals about the world (McKnight, 2000). In this way, the RGT serves as a holistic method to investigate a participant's view, rather than merely confirming specific isolated variables (Curtis et al., 2008; Gkouskos et al., 2014). The stages and processes of the method are well documented, as, for example, (Curtis et al., 2008; Hadley and Grogan, 2023). The RGT can be applied in an interview and can use elements to elicit bipolar personal constructs (Edwards et al., 2009). To illustrate this method, we might consider how a person perceives three different barbers. If they consider two barbers inexpensive and one expensive, the construct 'cheap–expensive' is formed. If the person can choose three barbershops that they would wish to compare, this is referred to as elicited elements. Conversely, if the researchers would provide what shops should be compared, this would be called supplied elements (Edwards et al., 2009; Rahman et al., 2022).

The RGT has been applied in a variety of domains. Regarding road design, the method was applied in 1988 to provide insight into subjective road categorization (Riemersma, 1988) and more recently into the perception of cycling infrastructure (Berghoefer and Vollrath, 2022). Hassenzahl and Trautmann (2001) applied the RGT in 2001 to analyze perceptions and preferences for German banking website designs. Lallemand and Koenig (2017) used it to explore how people perceive learning spaces through images and suggested that virtual reality (VR) could be a promising tool for future RGT studies, helping balance logistic constraints with experiential richness. The RGT method has also been applied to evaluate criteria for a novel design, such as the design of shape-changing interfaces (Kwak et al., 2014), convenient in-car passenger experiences (Berger et al., 2021) and user needs for future vehicles (Gkouskos et al., 2014). In both information systems research and the built environment, the RGT has been extensively applied, resulting in a substantial body of work. This includes both comprehensive field overviews (Curtis et al., 2008) and systematic literature reviews (Rahman et al., 2022), demonstrating its status as a well-established and validated research method.

1.1. Contribution

This research investigates the underexplored area of perceived uncertainty from the perspective of pedestrians, cyclists, and drivers of a manual car when interacting with an AV. Using a combination of VR-based and elicited scenarios, participants can generate constructs. These generated constructs and their overarching dimensions are used to give a structured understanding of the factors that contribute to uncertainty. In addition, we offer information on the relative influence of these factors and their specificity to AVs. This knowledge can be used to inform the design of eHMIs to provide information during uncertain situations. In addition, the factors that influence uncertainty can be included in scenarios for eHMI testing for diversification.

2. Method

The exact stimuli, research procedure, surveys used, and data collected are shared for transparency and reproducibility. For more details, see the supplementary material section.

2.1. Participants

This study was conducted with 25 participants (13 males and 12 females). The study's sample size is based on considerations for achieving saturation, since a sample size of 15–25 frequently is sufficient to capture the diversity of constructs within a given field in RGT studies (Tan and Hunter, 2002). Participants were recruited through convenience sampling (Robinson, 2014). As the study was conducted in the Netherlands, all recruited participants were residents of the Netherlands. All sessions were conducted in the same controlled lab environment at Eindhoven University of Technology following approval by the university's Ethical Review Board. Only adults who possessed a valid car driving license were allowed to participate. Additionally, participants who indicated that they were prone to VR sickness were excluded. Prior experience with AVs or VR was not required.

There were (16) participants in the age group of 24–29 and (9) in the age group of 30–39. The participants received a €15 gift voucher as compensation for their time. In terms of the origin of the participants, (8) reported coming from the Netherlands, (5) from China, (2) from Germany, (2) from India, and (1) from Colombia, Mexico, Indonesia, Italy, Iran, France, Romania, and Vietnam.

When asked to review a statement about their desire to ride in an AV (defined to participants in this study as "cars that fully perform all actions related to driving a car, also called self-driving cars"), participants generally showed a positive attitude (5-point Likert from -2 to +2, $M = 0.64$, $SD = 1.15$). Regarding past experience with vehicle automation, (2) participants reported having had a ride in an automated vehicle, no participants encountered an automated vehicle while driving, (13) have experience with automated driving functions (e.g., adaptive cruise control), (2) work in an AV related field, and (16) reported never having used or been inside an AV.

All participants were in possession of a valid car driver's license, which they had for (1) less than one year, (3) one to three years, (16) four to ten years, and (5) more than 10 years. During the past 12 months, (2) participants did not drive a car, (15) drove less than once a month, (2) once a month to once a week, (4) one to three days a week, and (2) even more often. The following two questions were answered by n=24, due to missing answers from one participant. During the past 12 months, (5) participants cycled once a month to once a week, (5) one to three days a week, (7) four to six days a week and (7) every day. Regarding the frequency of being a pedestrian, (1) participant reported being a pedestrian once a month to once a week, (4) one to three days a week, (8) four to six days a week, and (11) every day.

VR was reported to be unknown and never used by (1) participant, (3) reported having heard of VR but never having used it, (10) having used VR once or twice, (6) three to ten times, (5) more than ten times. On the Inclusion of Technology Affinity in Self-Scale (ITAS) (Henrich et al., 2022), participants indicated a high technological affinity with a mean score of 5.24 (SD=1.36, on a scale of 1–7).

2.2. Elements

As explained, in the RGT participants compare elements (such as experiences or objects) to extract personal constructs. This study opted for an approach that combined two elements that were elicited from the participants (i.e. participant-defined scenarios) and four elements supplied by researchers (i.e. VR scenarios), this usage of elicited and supplied elements is comparable to previous work (Berger et al., 2021). Although there are no strict criteria for the number of elements for RGT, the usage of around six elements is well accepted in the literature

(Hassenzahl and Trautmann, 2001, Kwak et al., 2014, Berger et al., 2021). The elements provided were used to allow participants to experience scenarios possible with SAE Level 4 or 5 AVs (e.g., a vehicle without passengers) (SAE International, 2021). The visuals (no soundscape) of the encounters between AVs and ORUs were created in Unity3D [1]. As a basis, we utilized the open source simulation environment of Bazilinskyy et al. (Bazilinskyy et al., 2020) in combination with additional Unity assets to add diversity to the scenarios. The four generated video scenarios, from now on referred to as the provided elements, were intentionally designed with varying properties in the traffic encounters (e.g., different road setups, transport modes, car models, and positions), allowing participants to create constructs around variables that actually influenced their uncertainty, see Fig. 2. This heterogeneity was intentionally leveraged to enable participants to generate a variety of constructs (Hassenzahl and Trautmann, 2001, Kwak et al., 2014).

The participants rated their VR experience of the supplied elements on the IPQ scale (0–6) with a presence of M = 4.20 (SD = 1.35), spatial presence M = 4.04 (SD = 1.16), involvement M = 3.71 (SD = 1.12) and experienced realism M = 2.43 (SD = 0.92) (igroup, 2023). Interpretation of these ratings using the work of Melo et al. (Melo et al., 2023) shows "acceptable" overall presence, "marginally acceptable" spatial presence and involvement, and "not acceptable" experienced realism.

For the objective of exploring constructs within a research area, elicited elements were added, as they can offer a deeper level of insight and are particularly suited for exploratory studies (Edwards et al., 2009). Furthermore, these elements can further lead to more of the aforementioned heterogeneity for generating constructs. In this study, participants generated two scenario descriptions that represented imaginary extremes (Curtis et al., 2008). One scenario was based on an encounter 'filled with uncertainty', whereas the other was 'filled with certainty'. To support participants in defining their elements, structured cards were provided, referred to in literature as role lists (Curtis et al., 2008; Rahman et al., 2022). The cards were set up to keep the elements focused on interactions between AVs and ORUs, and (un)certainty. Participants were encouraged to draw upon their traffic experience, with the goal of defining scenarios that could happen in the real world. For an example of cards demonstrating the elements elicited from a participant, see Fig. 1. Table 1 provides an overview of all the types of elements used in this study: four elements supplied by the researchers, and the two elements that were elicited from the participants.

2.3. Experimental procedure

The experimental procedure is visualized in Fig. 3, and was scheduled to last a maximum of 90 minutes. Participants completed their informed consent forms, after which they received further instructions about the study. AVs were explained to participants as cars that perform all actions related to driving a car. Then, they were asked to fill out a demographic questionnaire. Participants were presented with three sample scenarios to familiarize themselves with the VR headset and the digital environment. This way, participants already placed the VR headset in a comfortable position and could become familiar with the headset. To then become familiar with the RGT, the participants were guided in applying this method to the sample scenarios. More specifically, the participants were shown how each scenario was represented by a card with an image of that scenario; see Fig. 3. Then, they were asked what part regarding the road setup was similar within two of the scenarios but how this was different from a third one. For example, two scenarios could have a zebra crossing, and a third scenario could lack such a crossing. This could lead to constructs (sets of descriptive words) being generated that would then focus on the (lack of) presence of a zebra crossing. By discussing how two elements were similar and different from another element, participants were introduced to the formation of triads, which can be part of the RGT. Using triads for comparison generally leads to more cognitively complex and meaningful constructs compared to only comparing two elements (dyads) (Reddy and Caputi, 1999). This task was performed twice, so participants became familiar with the usage of the elements to generate constructs.

For clarity, the researcher reminded the participants once more of the definition of AVs. The participants were then informed that during this study they would be asked to compare scenarios with regard to factors that influenced their uncertainty. The meaning of uncertainty for this study was introduced in a standardized way as "an internal mental state resulting from the perceived inability to predict outcomes accurately" (based on (Milliken, 1987; Grupe and Nitschke, 2013)). To further clarify, this was illustrated with a practical example outside of the context of this study: "If you wish to visit a theme park this Sunday but are unsure if the theme park is open on Sundays, then you might experience uncertainty".

2.3.1. Element elicitation

The participants first started to generate their two imaginary self-defined encounters between an AV and another road user: one filled with uncertainty and one filled with certainty. This was done on the structured cards, where participants were asked to answer the questions and were invited to also draw the scenario. The participant then explained both self-defined scenarios to clarify these to the researcher.

2.4. Element observation

After the elicitation phase, participants were introduced to the supplied elements. The researcher explained that, within the context of the study, the AV could be identified in the videos by the blue color of a car. The supplied elements were presented in a counterbalanced order as 360-degree videos of a virtual environment created in Unity3D. These videos were viewed using a Meta Quest 3 head-mounted display, which played the locally stored high-resolution content (rendered from Unity at 8192 × 4096 pixels, 60 frames per second).

To gain insight into the quality of 360-degree videos, we measured Presence using the Igroup Presence Questionnaire using a 7-point Likert scale (igroup, 2023). The IPQ questionnaire was chosen because this measure has high reliability in a short time frame (Schwind et al., 2019). The questionnaire and later reported RGT steps were completed outside of VR to avoid discomfort that could be caused by the extensive wear of the head-mounted display.

2.4.1. Construct generation

To form diverse triads, both the elicited and supplied elements were represented on same sized paper cards that were placed facing down and shuffled, from which the participants then selected three cards (Hadley and Grogan, 2023; Tu et al., 2018). The participant would then use the triad to determine how two cards were similar and a third card was different with regard to a factor influencing uncertainty and would explain this to the researcher, as practiced during the familiarization phase. In case the constructs were unclear to the researcher, the so-called laddering was used, which is a technique to explore the rationale for, the meaning of, and the relationship between the constructs with the participant (Curtis et al., 2008). To assist in the experiment, neutral laddering questions were created before the experiment to provide inspiration to the researcher, with the aim of avoiding steering participants during this phase (e.g., "What do you mean by [construct]?"). When a construct would be clear, participants were asked which pole of the construct was linked with uncertainty, and the final constructs were noted accordingly by the researcher in Microsoft Excel.

The participants were then asked if they could form another triad with the same three elements until they could no longer think of new constructs. Subsequently, the selected cards were added back together with all the element cards, shuffled, and the process was started again. After the participant could no longer generate new constructs using

[1] https://unity.com/, last accessed 2025-02-03

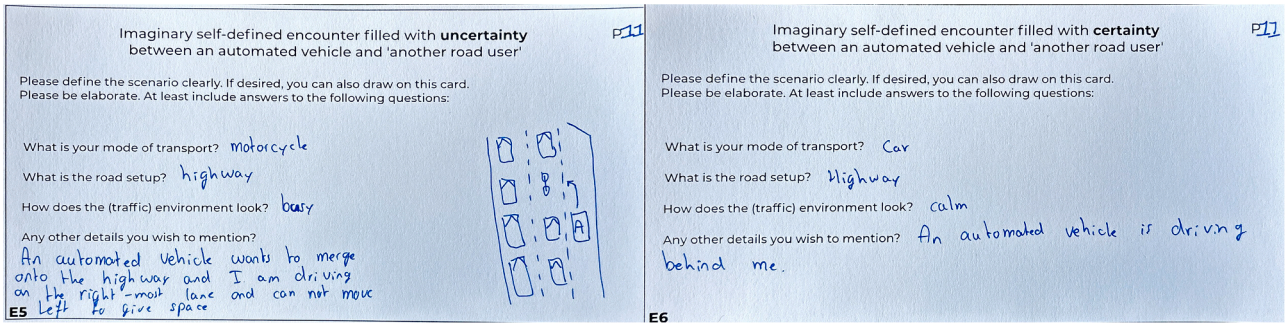


Fig. 1. Example of two elements elicited from participants: one focused on uncertainty and one on certainty.

Table 1
Description of the elements and whether they were elicited or supplied.

Description	Nature
1. A pedestrian crosses at a signalized crossing as a driverless AV approaches and brakes late.	Supplied
2. A cyclist encounters an approaching AV at night on a narrow residential street, where the AV must enter the opposing lane to drive around a police car and construction cones.	Supplied
3. A driver travels alongside an AV through a city street where an unloading truck partially blocks the path of the AV.	Supplied
4. A pedestrian crosses an unsignalized road as a small AV carrying a passenger approaches and a cat crosses the road.	Supplied
5. Imaginary self-defined encounter filled with uncertainty between an AV and another road user.	Elicited
6. Imaginary self-defined encounter filled with certainty between an AV and another road user.	Elicited

randomly formed triads, all elements cards were placed face up to provide the participants with a final opportunity to select elements for comparison in unprecedented configurations.

2.4.2. Confirmation and rating of the constructs

After having finished generating constructs, participants reviewed their list of constructs to verify that each accurately reflected their perceptions of uncertainty in scenarios involving AVs (Curtis et al., 2008). Participants were given the opportunity to revise or remove constructs if they felt any were inaccurate or redundant. Participants did not rate all elements against all constructs. Instead, they rated each construct on two dimensions using a 5-point Likert scale: (1) the importance of the construct in contributing to their sense of uncertainty, and (2) the uniqueness of the construct in relation to AVs (see Table 2). This methodological choice was based on the exploratory nature of the study, which focused on identifying and qualitatively examining the constructs that participants perceived as influencing uncertainty. We therefore did not aim to quantify relationships between elements and, consistent with comparable research (Lallemand and Koenig, 2017; Berger et al., 2021), did not ask participants to rate all elements against each elicited construct.

2.5. Analysis

The generated constructs were analyzed using qualitative content analysis, comparable to existing research (Curtis et al., 2008, Berger et al., 2021). Inductive coding (Linneberg and Korsgaard, 2019) was applied by two inside coders (having knowledge of the experiment) in Microsoft Excel (Lazar et al., 2017).

The codes were induced using constructs from four random data samples (20% per sample). For validity, all constructs received at least one (or multiple) code (Lazar et al., 2017). For example, a construct referring to a possible AV malfunction due to ORUs breaking traffic rules could be coded as relating to *Rule following* and *Operating proficiency*. The applied code is in the supplementary material for this study. Coding was performed with 73% agreement between the independent coders, resulting in a Kappa of 0.72 (Brennan and Prediger variant (Brennan and Prediger, 1981)), labeling the result as "substantial" (Kuckartz et al., 2019). Finally, disagreements in the coding of the individual analysis



Fig. 2. Overview of the supplied elements, numbers matching the numbers assigned in Table 1.

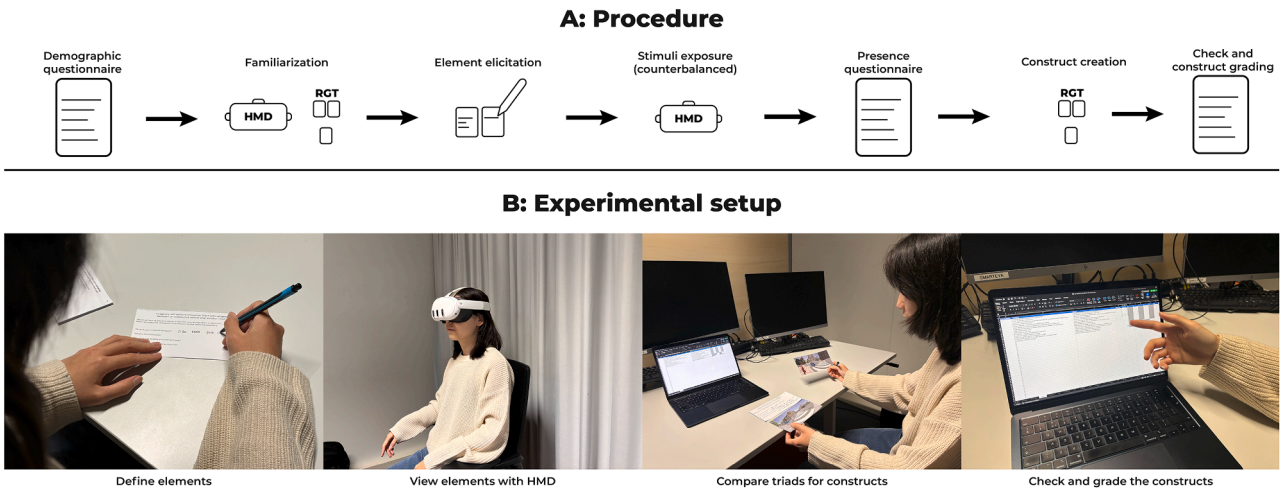


Fig. 3. (A) the procedure followed during the study and (B) the experimental setup.

Table 2
Questions for rating the generated constructs. Likert scale from (1) Strongly disagree – (5) Strongly agree.

Type	Question
Uniqueness for AVs	"[Construct pole A]" – "[Construct pole B]" is unique for scenarios with automated vehicles.
Influence on Uncertainty	"[Construct pole A]" – "[Construct pole B]" greatly influences my uncertainty.

were resolved on a common agreement basis between the two coders.

3. Results

3.1. Elicited constructs

In total, this study elicited 275 constructs. On average, the participants generated 11 constructs (SD = 2.20, minimum = 8, maximum = 16). Inductive qualitative content analysis (where each construct received at least one code for validity) performed by the two coders demonstrated the existence of 5 themes with 23 underlying codes; see Table 3.

3.2. Themes and codes

The theme ***Environment*** (141 constructs) included codes that pertain to the physical environment of traffic situations (e.g., *Road layout* or *Weather*). The code *Obstacle* (8) included the presence of animals or other blockings of the road. The code *Road width* (8) was attached to constructs that contrasted more narrow roads with wider (often multi-lane) roads. The code of *Road layout* (23) included different road layouts, such as the presence of merging lanes, road crossings, and cycling lane separations. The most-mentioned code was *Rule effectuation* (37), which related to characteristics present in the environment to communicate or enforce rules, such as traffic lights, signs, and lane markings. Constructs related to (not) being blocked by your environment, were coded as *Flexibility to maneuver* (17). *Perceivability* (27) referred to both the ability to perceive and to be perceived, which could be influenced by factors such as visual obstructions (e.g., objects blocking the line of sight) or environmental conditions like weather. The *Amount of actors* (21) included but was not limited to the influence of (many) pedestrians or (automated) vehicles.

The theme ***Communication/signaling*** (24) contains remarks about communication between traffic actors. Explicit communication of a future own action was coded as *Explicit signal (allocentric)* (4). Explicit communication of other's future actions (e.g. an AV showing a pedestrian that they can cross the road) were coded as *Explicit signal (egocentric)* (1). Constructs relating to abrupt braking were coded as an *Implicit signal (allocentric)* (13). Nonspecific mentions of signals (e.g., participants mentioning in general that a car would show it would stop, but not specify how this would be shown) were coded as *Signal - Undefined* (6).

The ***Subjective evaluation*** (108) theme consists of the interpretations of the participants of a situation. Coding in the category of *Commonness of scenario* (14) discusses the evaluations of the participants on commonness. The participants mentioned the relevance of their *Ability to predict* (48) how something would play out. Driving in a vehicle, related to a feeling of a lower *Perceived risk of harm* (27), compared to more vulnerable modes of transport such as cycling or walking. When constructs were formed around transport modes having relatively good brakes (such as a car), or being nimble (such as bikes), this was coded as the *Ability to intervene* (11). The features showing a vehicle is automated lead to an *Evaluable appearance* for the participants (8).

Within the theme ***Behavior and performance*** (54) participants mentioned ORUs (lack of) *Rule following* (12). The code *Speed* (13) concerned both own and others' their (relative) speed. The code *Workload* (2) discusses multiple mental tasks. Participants mentioned the need for an (urgent) *Act required* (11) as well. The code *Operating proficiency* (16) was the most-mentioned in this theme, and discussed the ability to operate properly in traffic.

Within the theme ***Social dynamics*** (15), constructs regarding (the lack of) the presence of a person in a self-driving vehicle were coded as *Human in AV* (9). The constructs concerning social influences by other humans were coded as *Social setting* (6).

3.3. Uniqueness for AVs and influence on uncertainty

Ratings of the influence of a construct on uncertainty and uniqueness of a construct for interactions with AVs were combined with the results of the thematic analysis to understand how themes and codes perform on these scales. For an overview of the numerical results, see Table 4 and Fig. 4. The following section will further detail what poles of constructs within each code were generally related to uncertainty or to certainty.

Within the theme of ***Environment***, the uniqueness is rated with M = 2.58, SD = 1.20 and influence M = 3.73, SD = 0.97. Constructs coded as *Obstacle* showed that the presence of an obstacle is related to uncertainty. *Road width* shows that wider roads are most often related to uncertainty. *Road layout* shows that (among other factors) merged roads with a lack of separations and that the presence of intersections both link to the pole of uncertainty. Regarding *Rule effectuation,* a lack of features

Table 3
Overview of themes, codes, their number of constructs and the percentage of participants that mentioned the construct.

Theme	Code	Number of constructs	Percentage of participants (%)
Environment	Obstacle	8	32
	Road width	8	32
	Road layout	23	56
	Rule effectuation	37	80
	Flexibility to maneuver	17	56
	Perceivability	27	68
	Amount of actors	21	56
Communication/signaling	Explicit signal (allocentric)	4	16
	Explicit signal (egocentric)	1	4
	Implicit signal (allocentric)	13	44
	Signal - Undefined	6	16
Subjective evaluation	Commonness of scenario	14	48
	Ability to predict	48	84
	Perceived risk of harm	27	72
	Ability to intervene	11	40
	Evaluable appearance	8	32
Behavior and performance	Rule following	12	40
	Speed	13	52
	Workload	2	8
	Act required	11	20
	Operating proficiency	16	32
Social dynamics	Human in AV	9	36
	Social setting	6	20

Table 4
Ratings per code about uniqueness for automated vehicles and influence on uncertainty (5-point Likert from 1 to 5).

Theme	Code	Uniqueness for AVs		Influence on uncertainty	
		Mean	SD	Mean	SD
Environment	Obstacle	3.38	1.51	3.63	1.06
	Road width	2.38	0.74	3.00	1.07
	Road layout	2.48	0.99	4.09	0.67
	Rule effectuation	2.95	1.33	3.59	1.07
	Flexibility to maneuver	2.41	1.00	3.59	1.00
	Perceivability	2.30	1.20	3.59	0.97
	Amount of actors	2.33	1.15	4.19	0.75
Communication/ signaling	Explicit signal (allocentric)	3.00	1.83	4.50	0.58
	Explicit signal (egocentric)	2.00	-	5.00	-
	Implicit signal (allocentric)	2.62	1.12	4.46	0.52
	Signal - Undefined	2.50	0.84	3.67	1.03
Subjective evaluation	Commonness of scenario	3.07	1.44	4.00	0.68
	Ability to predict	3.02	1.28	4.08	0.74
	Perceived risk of harm	1.89	1.12	3.78	0.93
	Ability to intervene	2.00	1.26	3.73	1.01
	Evaluable appearance	4.13	1.46	4.13	1.36
Behavior and performance	Rule following	2.75	1.22	4.17	1.03
	Speed	2.62	1.50	3.85	1.07
	Workload	3.00	1.41	4.00	1.41
	Act required	2.55	1.29	3.73	1.27
	Operating proficiency	4.25	1.13	3.75	1.00
Social dynamics	Human in AV	4.00	1.32	4.33	0.50
	Social setting	2.00	0.89	3.50	0.84

to communicate rules is related to uncertainty. A lack of own *Flexibility to maneuver* is related to uncertainty. Contrasting this, when other traffic participants had flexibility for a variety of maneuvers, this linked to uncertainty as well. Low *Perceivability* due to environmental conditions links with uncertainty. Additionally, not being in a car was linked to uncertainty by participants who wondered if they would be sufficiently perceivable for an AV. A higher *Amount of actors* related to uncertainty.

Regarding the theme ***Communication/signaling***, uniqueness $M = 2.63$, $SD = 1.13$, influence $M = 4.29$, $SD = 0.75$. the lack of or confusing usage of an *Explicit signal (allocentric)* linked to uncertainty. A lack of *Signal - Undefined* and *Explicit signal (egocentric)* also related to uncertainty. When a vehicle does not slow down gradually but suddenly brakes, this also links to uncertainty, as was seen in *Implicit signal (allocentric)*.

Within the theme of ***Subjective evaluation***, uniqueness $M = 2.72$, $SD = 1.41$, influence $M = 3.96$, $SD = 0.86$. A low *Commonness of scenario* linked to uncertainty. A high *Ability to predict* is positively related to certainty, whereas not being able to predict the outcome at all, or having multiple competing predictions relates to uncertainty. When experiencing a low(er) *Perceived risk of harm* (e.g. in a vehicle), this was positively related to certainty, whereas being a more vulnerable pedestrian or cyclist linked with uncertainty. Constructs in *Commonness of the scenario* show that irregular situations were related to uncertainty. A higher *Ability to intervene* is related to certainty. Results regarding an *Evaluable appearance* are mixed, based on what participants were trying to evaluate (e.g., evaluations could regard if a vehicle looked like an AV, or if it looked fast).

The theme of ***Behavior and performance*** is rated with a uniqueness $M = 3.13$, $SD = 1.44$, and influence of $M = 3.87$, $SD = 1.06$. A lack of *Rule following* by ORUs related to uncertainty. A higher (relative) *Speed* is related to increased uncertainty. A higher *Workload* was linked with uncertainty. When there is an *Act required*, compared to not needing to

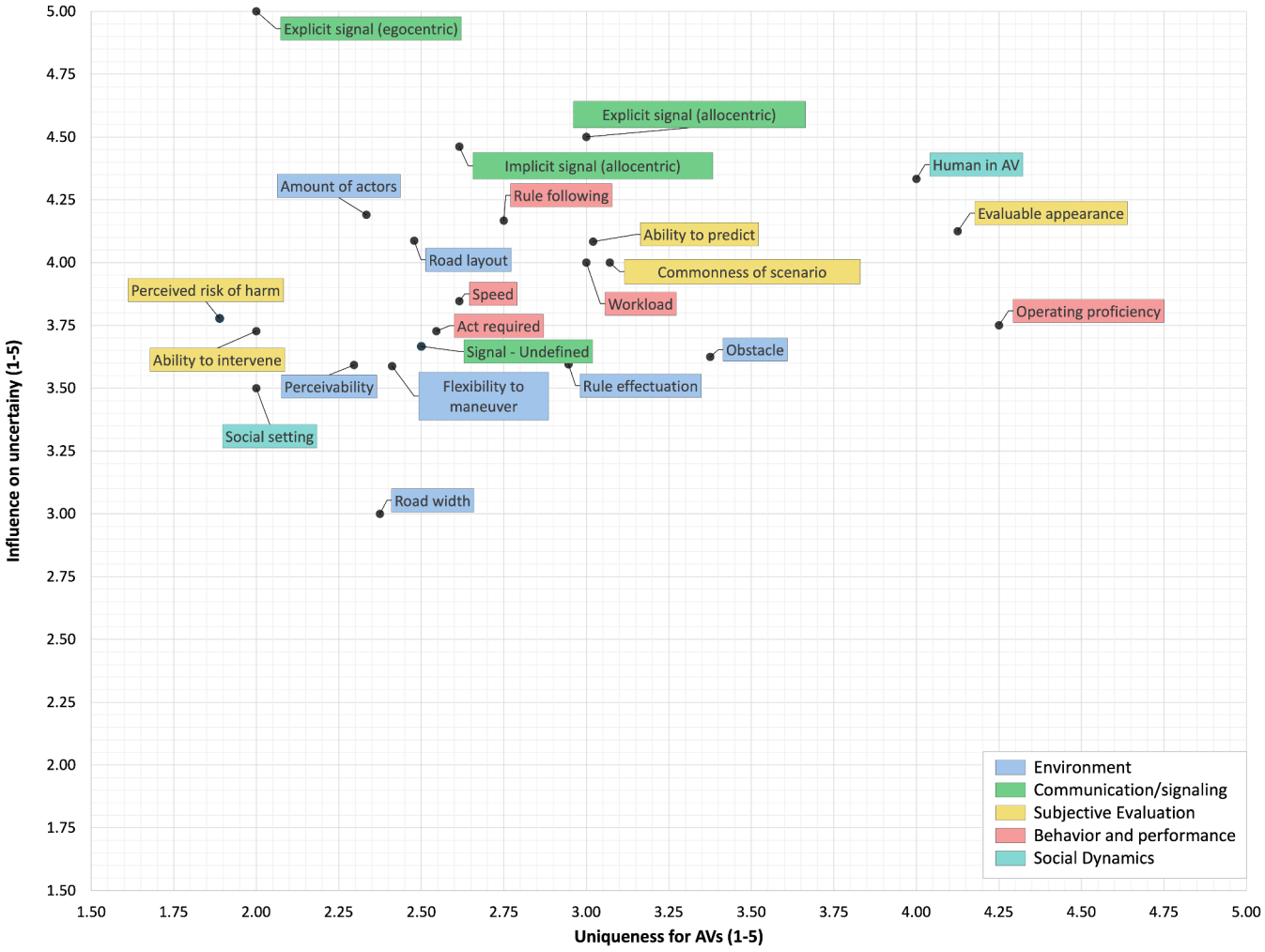


Fig. 4. Scatterplot of codes, color coded per theme.

perform any actions, this increases uncertainty. When estimating a bad *Operating proficiency* (e.g. considering a vehicle is not able to deal with a situation), this is linked with uncertainty.

Regarding the theme ***Social dynamics***, uniqueness M = 3.20, SD = 1.52, influence M = 4.00, SD = 0.76. Not having a *Human in AV* was related to uncertainty. For *social setting*, a lack of others in a similar role in a scenario (e.g. other pedestrians also waiting to cross the road) was related to uncertainty.

4. Discussion

Human uncertainty is associated with negative emotional states and negatively influences the ability to make a decision (Phillips-Wren and Adya, 2020; Morriss et al., 2022; Franssen et al., 2024). We researched this in the context of ORUs, since uncertainty could be provoked by AVs, which could lack the ability of explicit communication and might have different driving styles compared to human driving (Bellem et al., 2018; Bazilinskyy et al., 2021;Sucha et al., 2017). Gaining insight into factors that lead to uncertainty is of importance to understand when AVs could present additional information to address human needs (e.g. using an eHMI), since experiencing uncertainty promotes information seeking (Kramer, 1999; Keller et al., 2020). To explore this, we conducted an RGT study which allowed participants to compare scenarios with respect to the differences that influenced their uncertainty. Participants were shown four heterogeneous scenarios of interactions with AVs, and could also self-define two scenarios.

Several factors identified in this study have previously been reported in the AV literature. Prior work has shown the importance of signaling and implicit communication based on vehicle motion patterns from other work (Dey and Terken, 2017, Risto et al., 2017; Sripada et al., 2021). Similarly, Boelhouwer et al. (Boelhouwer et al., 2020) found that infrastructure, traffic types, and road types influence scenario complexity and considered that familiarity could have played a role in their findings. Our results are consistent with this earlier work and show that these factors are likewise associated with uncertainty during encounters with AVs.

By applying the RGT to the study of uncertainty in AV encounters, participants were able to define and evaluate uncertainty through their own constructs rather than through researcher-imposed categories. This participant-driven approach offered a new means of investigating uncertainty and complements existing approaches that typically focus on predefined variables or existing theoretical dimensions.

Beyond commonly studied factors, participants identified constructs such as flexibility to maneuver, commonness of the scenario, social setting, and the perceived ability to intervene. These findings suggest that uncertainty is shaped by a broader set of contextual and social influences than typically considered in studies focusing primarily on AV communication. Furthermore, by collecting ratings of both influence on uncertainty and uniqueness for AVs, the study provides insight into which factors appear specific to automated driving and which reflect broader characteristics of traffic interactions.

4.1. Implications for uncertainty management

Based on the number of participants' mentions and the influence on uncertainty, we define three main directions for considering uncertainty.

4.1.1. Holistic approach towards communication and interaction needs

The variety of themes identified in our study demonstrates the interconnected nature of how ORUs experience uncertainty in traffic interactions. Therefore, we consider that solutions aimed at managing uncertainty should take a holistic approach. Factors influencing uncertainty may not occur in isolation, and their presence and relative importance may vary across situations. For example, one could imagine a cyclist traveling on a narrow, winding mountain road in rainy conditions, surrounded by mixed traffic moving at higher speeds. In such a scenario, limited perceivability, constrained flexibility to maneuver and unclear road markings may simultaneously contribute to uncertainty. Designing solutions for these situations therefore requires consideration of the complexity of real-world traffic interactions. This contrasts with much existing AV research, such as eHMI studies, which have typically evaluated designs in good lighting conditions and a limited set of traffic scenarios (Dey et al., 2020). Our findings provide a structured overview of the diverse factors that can contribute to uncertainty and highlight the importance of considering how these factors interact. Therefore, we argue that uncertainty should be approached holistically rather than through isolated factors alone. Such a holistic approach should furthermore consider aspects such as switching between traffic roles and unified HMI communication strategies, as discussed by other researchers (Gao et al., 2024; Bengler et al., 2020; Verstegen et al., 2024; Dong et al., 2024).

4.1.2. The influence of the built environment

Our findings demonstrate that features present in the built environment influence uncertainty, such as the *Road layout*, the *Flexibility to maneuver*, features for *Rule effectuation*, and that sharing the road with a large *Amount of actors*. The built environment has a wide range of factors that could be adjusted in order to manage uncertainty. For example, improving road surface markings (e.g., lane lines and edge lines) might be a feasible solution to decrease uncertainty of ORUs. Not only could adjustments be used to reduce uncertainty for ORUs, AVs might anyhow require adjustments and improvements to road infrastructure to adjust their behavior accordingly (Liu et al., 2019). Similarly, characteristics in the build environment already can be used to influence driver speeds (Schepers et al., 2025). However, due to logistical and financial reasons, adjustments in the built environment cannot solely be a solution to manage uncertainty. For example, implementing physical road separations might make road users more certain about what other traffic can (not) do. But it may be impractical due to cost and space requirements. Therefore, we still consider that addressing uncertainty-inducing factors through communication strategies (i.e., using eHMIs) may be a viable complementary solution.

4.1.3. Standardization to build human expectations

Based on our findings regarding the commonness of a scenario and the ability to predict, one should understand the importance of past experiences and predictability on uncertainty for ORUs. Based on this, we argue for the importance of standardization and rules to build expectations.

For this reason, we consider the application of standardization important. Firstly, governmental/legal requirements could be applied to let AV manufacturers standardize communication behavior. Already for in-vehicle HMIs, standardization and design guidance is being developed for SAE Level 2 and 3 automation (e.g., see Campbell et al. (Campbell et al., 2018) for an overview). For communication with ORUs, however, current regulations (for example, see the United States [2] and Europe [3]) focus on the standardization of lights. We consider such regulations regarding communication methods with ORUs should be further expanded to standardize communication during the transition towards automation. This can be seen as an extension upon how indicators or braking lights have been standardized in the past.

Likewise, our findings underscore that a lack of rule following leads to uncertainty. Therefore, we consider that rules could be further expanded and leveraged to further increase expected behavior. In specific, unstructured situations that present high uncertainty, solutions could focus on direct effectuation and optionally enforcement, such as placing traffic lights. Indirect effectuation, such as improving and adapting education by adding a section about interactions with AVs for drivers license tests or in education to young children should also be considered. Conversely, how AVs follow rules should be considered as well. For example, sudden braking to a full halt, present in *Implicit signal (allocentric)* was related to uncertainty. Other work shows similar findings, where such behavior did not meet human norms and led to dangerous situations both for occupants and other road users (Pelikan, 2021).

4.2. AV-specific and general traffic uncertainty

Our findings indicate that the uncertainty present in interactions with AVs is not entirely new. Ratings of "Uniqueness for AVs" show that only 6 of the 23 codes scored above the scale midpoint (>3 on a 5-point Likert scale), suggesting that most identified factors were not perceived as unique to AVs. Factors with low uniqueness ratings may therefore also contribute to uncertainty in general interactions not specifically related to AVs. Despite these factors not being unique to AVs, the introduction of AVs could still change the prevalence of these existing factors leading to uncertainty, as ORUs can no longer rely on familiar explicit cues and may have an incomplete understanding of how an AV will respond, particularly when its driving behavior differs from that of human drivers (Bellem et al., 2018; Bazilinskyy et al., 2021; Sucha et al., 2017). Six factors related to uncertainty were perceived as more specific to AV interactions: the obstacles on the road, scenario commonness, ability to predict, evaluable appearance, operating proficiency, and the presence or absence of a human in the vehicle. Therefore, implementation of AVs may lead to the experience of uncertainty caused by these factors. Although the present study did not systematically compare interactions with AVs and manually driven vehicles, the findings indicate that AVs do not create an entirely new set of factors leading to uncertainties. Instead, AV interactions combine general sources of traffic uncertainty with sources that are more specific to automation.

4.3. Limitations and future work

The RGT was used for the elicitation of constructs due to it being more transparent and its potential to reduce bias compared to alternative methods (Curtis et al., 2008). Though all qualitative analysis methods are inherently susceptible to bias (Lazar et al., 2017), the analysis sought to minimize this by applying a dual-coder approach for the analysis of all constructs (Lazar et al., 2017). The participants' relatively restricted age range, high technology affinity, limited experience with AVs, and low driving frequency may partly reflect the use of convenience sampling within the institutional context in which the study was conducted. These sample characteristics are boundary

[2] https://www.ecfr.gov/current/title-49/subtitle-B/chapter-V/part-571/subpart-B/section-571.108, last accessed 2025-06-20

[3] https://unece.org/transportvehicle-regulations/working-party-lighting-and-light-signalling-introduction, last accessed 2025-06-20

conditions that may limit the transferability of the findings to the broader population of ORUs. Factors contributing to uncertainty may differ among older or less technology-oriented road users, frequent drivers, and ORUs who regularly interact with AVs.

Given that participants were introduced to a definition of uncertainty that explicitly referred to predictability (Milliken, 1987; Grupe and Nitschke, 2013), the occurrence of constructs related to predictability may partly reflect this framing. Although the relationship between uncertainty and predictability is theoretically expected, future studies could examine whether predictability remains equally prominent when participants are provided with alternative definitions or are allowed to use the term uncertainty based on their own understanding. However, the primary contribution of the present study is not the observation that uncertainty and predictability are related, but rather the broader understanding of the factors associated with uncertainty.

Regarding the provided VR elements, overall presence in the virtual environment was rated as "acceptable", but the realism was rated as "not acceptable", these findings could relate to the fidelity of the used simulation software and the lack of a soundscape. For the purpose of this exploratory study, the elements could still be compared to elicit constructs, for which we consider that the realism was sufficient. Especially since the RGT originally does not depend on the usage of lived experiences (Lallemand and Koenig, 2017). Similarly, during the application of the RGT, previous research compared elements in the form of images or concept descriptions (Gkouskos et al., 2014; Riemersma, 1988; Berghoefer and Vollrath, 2022; Lallemand and Koenig, 2017).

Future research should verify the existence of the identified factors with participants with extensive real-life experience in interacting with AVs, since AV familiarity and the formation of appropriate mental models could have an influence on the factors contributing to the experienced user uncertainty. Such future research could be conducted in areas where AV services have been deployed, such as Waymo, who provides 250,000+ rides each week (Waymo n.d.). Such an approach utilizes the fact that everyday life experiences are all unique, this might further broaden the understanding of factors that influence uncertainty. Because there was no grid where every element was assessed against every construct, the present study could not quantitatively examine if and how the constructs differentiated individual scenarios. Future research could use such ratings to enable conventional quantitative grid-based comparisons. Such ratings could then be used to gain additional insights into patterns, similarities and underlying structures between elements and constructs, for example through multidimensional scaling, cluster analysis and principal component analysis (Curtis et al., 2008; Edwards et al., 2009).

Due to the holistic nature of the RGT (Curtis et al., 2008; Gkouskos et al., 2014), we consider it a promising method for future research on traffic interactions. For uncertainty specifically, the RGT acts as a tool to externalize a subject's view of the world (McKnight, 2000), however, the presence of uncertainty at lower levels of consciousness (that one might not be actively aware of) (Anderson et al., 2019), should be researched further as well since these cannot be externalized using the RGT. Future research should also test and refine the identified factors through controlled experiments that systematically manipulate individual factors to assess their effects on uncertainty.

Based on the negative influences uncertainty has on decision making and emotional states (Phillips-Wren and Adya, 2020; Morriss et al., 2022; Franssen et al., 2024) we propose three avenues to manage uncertainty: leveraging a holistic approach towards communication and interaction needs, adaptions in the built environment and the development of standardization. Since we consider that this management of uncertainty is underexplored, we caution against the practice of heedless solutions for uncertainty minimization. In ambiguous situations, excessive certainty may be unsafe, particularly in the context of mobility. Uncertainty should not be eliminated for its negative effects, but should be researched and managed in a thoughtful manner.

5. Conclusion

In this paper, we explore the perceived uncertainty from the perspective of ORUs encountering an AV. For this purpose, we let 25 participants self-define interactions with AVs and showed four heterogeneous traffic scenarios using VR in a counterbalanced manner. Using the RGT, participants compared these scenarios to elicit constructs that influenced their uncertainty.

Dual-coder thematic analysis of the constructs revealed 5 themes, which are environment, communication/signaling, (the participant's) subjective evaluation, behavior and performance, and social dynamics, based on 23 underlying codes. Based on participants' ratings of the constructs, we identified AV-specific and general sources of uncertainty, as well as their level of influence. Drawing on these insights, we present considerations for uncertainty management. We discuss how adaptations in the built environment and eHMI communication could be used as complementary tools for reducing uncertainty. Furthermore, we advocate for a holistic approach towards communication between AVs and ORUs and underline the importance of standardization and regulations to support the establishment of shared expectations in traffic interactions with AVs.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Microsoft Copilot in order to improve the language used in the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Rutger Verstegen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruolin Gao:** Visualization, Formal analysis, Data curation. **Pavlo Bazilinskyy:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Conceptualization. **Marieke Martens:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition.

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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Supplementary materials

The followed study protocol, video stimuli, references to the Unity assets used, unprocessed data and data codes steps are available at: https://doi.org/10.4121/db6bea0d-bad4-46fa-9004-9303de2eb535.

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