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1246: USER EXPERIENCE (UX) IN AV-HUMAN INTERACTION

Beyond intent: enhancing transparency in automated vehicle behaviour by visualising their connectivity

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Abstract

Enhancing transparency in automated vehicle (AV) behaviour can help pedestrians understand how AVs work, which builds trust and ensures safer interactions. As AVs increasingly operate as part of a coordinated network, it is important to make their connectivity clear, helping pedestrians anticipate AV behaviour on the road. This study uses a qualitative design exploration to investigate visual methods for conveying AV connectivity. In the first phase, design concepts were generated using a biomimicry approach, drawing inspiration from nature, such as the harmonious chirping of crickets. In the second phase, focus groups with 16 participants were conducted to gather new concept ideas and evaluate the biomimicry-inspired designs. Our findings suggest that network symbols (e.g., Wi-Fi signals) or graphical elements resembling these symbols (e.g., ripple waves) are more effective in communicating connectivity than abstract methods, such as light patterns moving in a coordinated manner across vehicles. Highly visible connectivity cues may enhance pedestrians' perceived safety, a promising area for future research. This research contributes to ongoing efforts in designing intuitive visual communication strategies for AVs, moving beyond intent communication to include how AVs function as a network.

Keywords Automated vehicles · External car displays · Human–machine interfaces · EHMIs · Vehicle–pedestrian communication · Scalability

1 Introduction

Automated vehicles (AVs) are transforming transportation, promising improved safety, efficiency, and mobility [28, 64]. As these vehicles increasingly share roadways with pedestrians, clear and consistent communication between Avs and pedestrians becomes essential to ensure safe interactions and foster public trust. External Human–Machine Interfaces (eHMIs)—such as LED displays showing messages like 'After You' to indicate it is safe

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to cross—have been widely explored to convey AV intents [21, 46, 59]. According to ISO/TR 23049:2018, eHMIs are a crucial element in AV design, reducing ambiguity and promoting harmonious interactions [30]. Designing effective eHMIs represents a critical Human–Computer Interaction (HCI) challenge, as it requires translating complex machine decision-making into intuitive, human-understandable signals.

While intent communication, which focuses on the immediate actions of AVs, is crucial, there is a growing need for pedestrians to understand how AVs operate and make decisions. For instance, eHMIs can convey a vehicle's intended trajectory [18, 19, 61] or its sensor awareness [10, 11, 46, 60], providing pedestrians with additional context. Similarly, as AVs increasingly operate within a connected vehicle network [32, 36, 44], they can coordinate and communicate as a cohesive unit on the road. However, this interconnected nature is largely unfamiliar to the public [15]; pedestrians may not intuitively understand that when one AV stops and signals to cross, other connected AVs will also respond accordingly, ensuring coordinated action. This lack of understanding has been shown to lower trust and increase cognitive load in interconnected AV communication, as *'people today think about every vehicle as a single unit'* and *'the effects of connectivity were unknown to the participants'* [15].

To bridge this knowledge gap, this study uses a qualitative design exploration to investigate how AV connectivity can be visually communicated, helping pedestrians anticipate AV behaviour more accurately. In the first phase, design concepts were generated using a biomimicry approach [4], drawing inspiration from nature, such as the harmonious chirping of crickets, to create intuitive representations of connectivity. The second phase involved online focus groups with 16 participants, who further contributed to the idea generation and evaluated the biomimicry-inspired designs. This approach integrates both researchers' insights and participants' preferences to identify effective visual elements for communicating AV connectivity.

Our study makes the following contributions:

- Provides insights into visual design elements that effectively convey AV connectivity, moving beyond intent communication to illustrate how AVs function as a network. This advances existing efforts to enhance transparency in AV behaviour.
- Highlights how visualising AV connectivity may improve pedestrians' perceived safety, offering a promising avenue for future research.
- Outlines potential research directions for the development of interconnected eHMIs.

2 Related work

2.1 External human–machine interfaces and beyond intent communication

As AV technology advances, the interaction between vehicles and human road users is evolving. This shift affects not only drivers and passengers but also pedestrians and other vulnerable road users [37, 54, 57]. eHMIs help bridge the communication gap created by the absence of human drivers, often providing information related to right-of-way negotiation [14, 21, 27]. They commonly focus on intent communication, signalling when an AV intends to stop, yield, or proceed. These signals can take various forms, including LED light bands [23, 35], LED screens [20, 26, 50], and laser projections [49, 52]. In line with Zileli et al. [71], these interfaces enhance transparency by giving pedestrians cues about the vehicle's immediate actions [71].

Beyond conveying intent, there is a growing need to help pedestrians understand how AVs operate and make decisions. In a related area, there is a body of work focused on designing interfaces that provide information about the decision-making processes of autonomous systems, including robots, to collaborators and observers [33, 41, 58, 63, 69]. These interfaces aim to increase transparency and trust by revealing the internal states and reasoning of these systems. For example, Yu et al. [70] investigated how displaying a pedestrian's predicted path could enhance understanding of a delivery robot's decision-making process. Their findings showed that the majority of participants felt that the visualisation improved their comprehension of how the robot 'thinks,' indicating that providing such information fosters clearer and safer interactions. Similarly, a number of eHMI concepts has examined methods to reveal aspects like the vehicle's intended trajectory [18, 19, 61] or sensor awareness [10, 11, 46, 60]. These concepts highlight the importance of not just signalling intent but also offering *contextual information* that contributes to a deeper understanding of AV behaviour. Our study advances this line of work by investigating how eHMIs can represent AVs as interconnected entities on the road.

2.2 Visualising connectivity between AVs

The potential of visualising AV connectivity becomes pronounced in complex traffic environments. In scenarios involving multiple AVs, a lack of coordinated communication among them can lead to confusion and increased cognitive load for pedestrians [24, 38]. Conflicting or overwhelming signals from multiple individual eHMIs can cause pedestrians to misinterpret intentions, resulting in unsafe crossing decisions. For instance, mixed messages may occur if one AV signals that it is safe to cross while other AVs do not stop [43, 45]. To mitigate these issues, researchers have leveraged vehicle-to-everything (V2X) communication systems [66] to enable harmonised and coordinated communication between vehicles, which forms the basis of interconnected eHMIs.

An interconnected eHMI system refers to a coordinated external communication interface across multiple AVs, allowing them to share information and present a unified message to pedestrians. For example, in multi-vehicle scenarios, one eHMI could be designated to communicate the collective intent of all nearby vehicles [15, 38]. Centralising communication through a single eHMI has the potential to reduce the cognitive load required to interpret multiple individual eHMIs [15], thereby improving pedestrian decision-making and traffic flow [38]. However, several technical and human factor challenges remain. A key issue stems from the existing mental model of perceiving each vehicle as an independent entity, making the concept of interconnected systems unfamiliar to pedestrians. This perception contributes to scepticism towards interconnected eHMI concepts [15], as well as their reluctance to use hand gestures to signal crossing intentions to AVs, assuming that only a limited number of nearby vehicles will be able to see and respond to their gestures [65]. These challenges highlight the need for visual design solutions that transparently convey AV connectivity, potentially enhancing pedestrian understanding and trust in interconnected eHMIs.

3 Methodology

Conveying connectivity between AVs introduces a novel perspective in the eHMI literature. To the best of our knowledge, this study is the first to explore how to visually communicate AV connectivity through eHMIs. We conducted a design exploration to investigate *'possibilities outside the current paradigms'* [29]. This qualitative approach captures the nuanced perceptions and ideas surrounding AV connectivity, allowing for the generation of rich insights. The process comprises two phases (see Fig. 1).

Phase 1—biomimicry concept generation Leveraging the researchers' design background and expertise in eHMIs, this phase employed a biomimicry approach [4] to explore how natural patterns could inspire eHMI concepts. Biomimicry has previously been applied to AVs (e.g., bio-inspired intent communication [53]) and bicycles (e.g., ad-hoc 'swarms' created through synchronised light pulsation [5, 6]). Building on this foundation, we developed initial design sketches that visually represented AV connectivity. These sketches then served as catalysts for the Phase 2 focus groups, facilitating deeper discussions on how to convey connectivity between AVs.

Phase 2—collaborative ideation and discussion This phase leveraged participants' insights to refine and expand upon the initial biomimicry-inspired concepts. The first activity, a brainwriting session, enabled participants to collaboratively brainstorm and contribute design ideas for conveying connectivity between AVs. The second activity involved presenting the concepts generated in Phase 1 for further discussion. The goal was not to determine whether the concepts were 'good' or 'bad,' but to use them as a means to understand participants' thought processes and gather ideas on how AV connectivity could be conveyed [42].

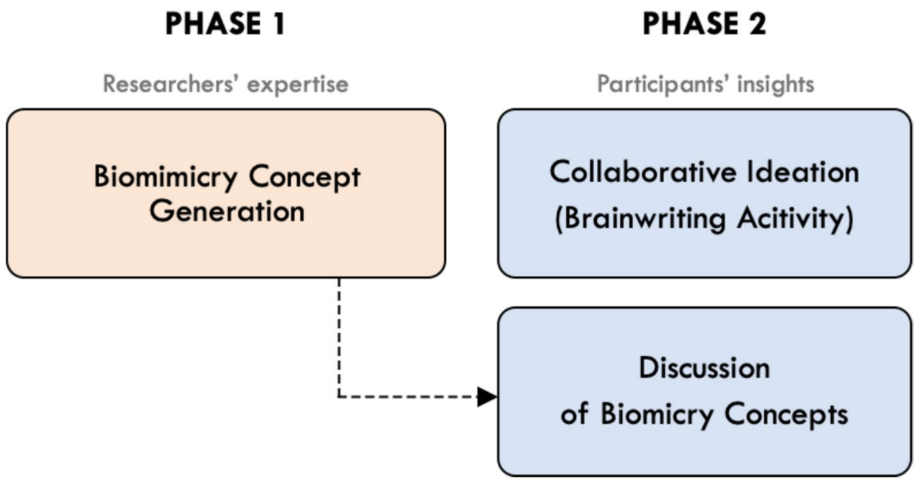
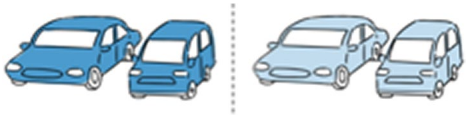


Fig. 1 Structure of the design exploration

Table 1 Overview of design concepts with descriptions and sketches

Synchronised Communication	
Pulsating Car Paint BMW unveiled the world's first colour-changing concept automobile in 2022 [31]. The concept car demonstrates the potential of E Ink technology, which can change colour when stimulated by an electrical impulse, providing drivers with a way to express themselves and reduce energy consumption. As a result, we implemented a uniform pulsating pattern to indicate the yielding intents; the sinusoidal pattern of increasing and decreasing brightness may be associated with a 'waiting' message Dey et al. [22].	
Inward Sweeping Light Band A popular eHMI form factor is the one-dimensional light band, characterised by its simplicity and ease of implementation within the current design language of a car [22]. This design concept is an approximation of the Bumper eHMI's yielding state [24], where the two light segments from the edge of the car bumper repeatedly sweep inwards. The animation sequence has the potential to communicate the connectivity aspect more clearly when the movement is synchronised.	
Projected Circular Wave AV illustrations commonly found on stock photography websites often feature a circular wave symbolising the vehicle's radar sensor system. Owing to its subtle and calming nature, this wave pattern has been used as the basis for several projection-based eHMI concepts [49, 52]. In our design, the projection is placed beneath the AVs, generating a ripple effect with the wave expanding outwards before gradually fading away.	
Coordinated Movement	
Chasing Lights This concept builds upon the LED light band placed on a vehicle's front bumper. It features a two-part light segment that moves back and forth between the eHMI displays, effectively communicating connectivity between AVs in multiple lanes.	

***Shortened Forms:** For ease of reference, concepts will be referred to as Pulsating, Sweeping, Wave, and Chasing in the remaining part of the paper.

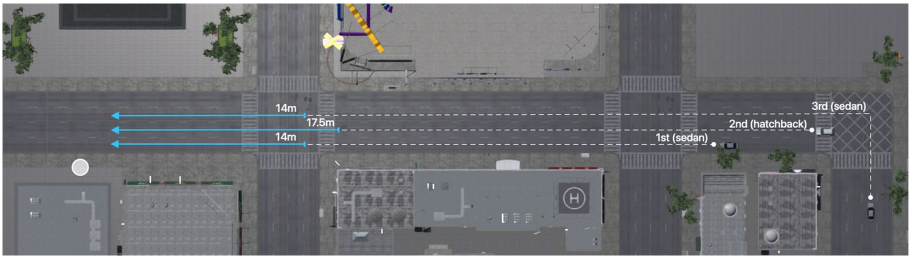


Fig. 2 Dotted white lines represent the driving paths of the vehicles. Solid blue arrows signify the points where each vehicle starts decelerating and eventually comes to a complete stop. The white circle denotes the pedestrian's position. The vehicles arrive in the sequence depicted in the figure

4 Phase 1 – biomimicry concept generation

4.1 Concept sketches

Drawing on a biomimicry approach, we took inspiration from natural swarms, observing features that could represent AVs operating in unison. Key characteristics like synchronised communication (e.g., fireflies' synchronised flashing, crickets' harmonious chirping) and coordinated movement (e.g., schools of fish, bird flocks) guided our design process. By integrating these natural patterns with existing eHMI design elements (e.g., abstract lighting and projection) [21], we created four concepts to express AV connectivity (see Table 1).

Synchronised communication In current traffic, perfect light symmetry in car signals is rare. For example, turn signals are legally required to blink at a steady rate of 1 to 2 Hz [40], but common flasher units often lack precision [17]. Variations in flash rates can be caused by factors such as voltage load changes, manufacturing tolerances, and mechanical wear, resulting in different signals rarely flashing in unison. This inconsistency presents an opportunity to use synchronised eHMI animation cycles as a visual representation of connectivity between AVs.

Coordinated movement The idea of combined displays was introduced by Colley et al. [13] in their design space for external car displays. They considered multi-vehicle displays in addition to single-car versions, highlighting the potential of coordinated visual cues. Building on this idea, our concept envisions digital graphic elements moving seamlessly between vehicles' displays, creating a dynamic sense of continuity and interconnectedness among AVs.

4.2 Animated video prototypes

To rapidly prototype our concepts, we created 3D representations using the Unity[1] game engine and 3D assets downloaded from the Unity Asset Store.[2] The virtual environment

[1] https://unity.com/
[2] https://assetstore.unity.com/

features a one-way four-lane city road. The camera was positioned to capture the perspective of a pedestrian waiting to cross the road at a section without zebra crossings. Two passenger car models were chosen: a white sedan and a light grey hatchback, which are similar in size and colour. Three vehicles were programmed to approach from the right-hand side at a speed of 20 km/h and subsequently decelerate within 5 s (1.11 m/s2) (sedan model) and 6.5 s (0.85 m/s2) (hatchback model) and come to a complete stop at a distance of 2 m from the pedestrian's location (see Fig. 2). We did not model any people in the vehicles to create a driverless perception. Additionally, we used an artificial engine sound for electric vehicles [2] rather than the typical gasoline engine noise. The pitch of the sound was programmed to change with speed.

In the simulated traffic scenario, two vehicles in the lanes closest to the pedestrian activate their eHMIs as they decelerate and come to a stop. After 5 s, a third vehicle comes into the pedestrian's view from a different lane, activating its eHMI in the same way as the previous two vehicles. The scenario concludes several seconds after the third vehicle has fully stopped. Each concept video, recorded from the Unity Editor in Play mode, is 60 s long and split into two parts: the first featuring nighttime scenery and the second daytime scenery (see Fig. 3). Apart from the lighting differences, the design concepts and vehicle behaviours remain consistent across both scenes. We included the night scene because it is generally more challenging for pedestrians to detect vehicles from a distance and observe their motion at night. Additionally, since all the proposed concepts are light-based, they might be affected by existing artificial light sources, such as streetlamps, illuminated buildings, or even the vehicles' own headlights.

In the *Pulsating* concept, a script was employed to control the colour and intensity of the emissive material, causing the car paint to change to cyan and pulse in brightness at a frequency of 0.285 Hz. For the light band concepts (*Sweeping* and *Chasing*), animation clips were created to accurately synchronise the positions of the light segments and their visibility within specific keyframes. As for the *Wave* concept, the ripple effect was generated using Unity's Particle System and an annulus (a ring shape) as the particle texture. A neutral colour, cyan [22], was utilised for all concepts, though the shade varied slightly among them.

Fig. 3 Screenshots of the four design concepts, with the eHMIs activated on two stopped vehicles. Top: Night scenes with illuminated buildings and vehicles' headlights. Bottom: Day scenes with ample daylight

5 Phase 2 – collaborative ideation and discussion

5.1 Participants

Sixteen participants (6 males, 10 females; aged 18–44) were recruited through the university's mailing lists, via social media networks, and by word of mouth. They took part in this study voluntarily and received no compensation. The study received approval from the Human Ethics Committee at the University of Sydney (ID 2020/779).

Of the participants, seven held a Bachelor's degree, nine held a Master's, and two held a Doctoral degree. All participants were fluent in English and represented a variety of nationalities, including Australian, New Zealander, Chinese, Hong Konger, Vietnamese, Thai, Colombian, Indian, Iranian, and Pakistani. Regarding transportation modes, four participants primarily used cars, three used bicycles or motorbikes, and the remaining relied on public transportation.

The participants were divided into two groups: design experts and non-designers. Two sessions included design experts (four user experience practitioners and four design researchers), while the other two featured non-designers (four postgraduate students from various fields, two researchers in intelligent transportation, and two business managers). This setup allowed us to collect diverse feedback from both design professionals and those without a design background.

Given the exploratory nature of this study, the focus was on generating rich insights rather than statistical generalisation. The sample size of 16 aligns with established qualitative research practices, particularly in automotive HCI research, where similar studies have used sample sizes ranging from 6 to 15 participants [12, 15, 45, 46, 56, 68]. Additionally, qualitative HCI studies typically report an average sample size of 12, with focus groups in CHI[3] research averaging 21 participants (SD = 7) [9]. Conducting four sequential sessions allowed us to track emerging trends and ensure *data saturation*—the point at which no new themes or insights emerge [48]—as themes became increasingly stable by the final session.

5.2 Procedure

Relevant demographic data on the participants' age group, gender, occupation, mode of transportation, driver's licence, nationality, the highest level of education, and English proficiency were collected via an online demographic questionnaire distributed to the study participants upon enrolment for screening and group allocation purposes. The focus group sessions were held online, with Zoom[4] serving as the video conferencing platform and Miro[5] serving as the digital whiteboarding tool. Each session lasted approximately 90 min.

Two researchers facilitated each session: the first author guided participants and moderated discussions, while the third author managed time and clarified comments. Three pilot studies with seven participants were conducted to refine the study protocol and data collection process. All focus group sessions followed a consistent agenda comprising three parts: an introduction, an idea-generation activity, and a discussion of the biomimicry concepts.

[3] The ACM Conference on Human Factors in Computing Systems (CHI) is a premier venue for HCI, including studies on emerging automotive interfaces and user experience.

[4] https://www.zoom.com/

[5] https://miro.com/

Introduction Participants introduced themselves and shared their prior experiences with AVs and pedestrian crossing behaviours. This was followed by a brief explanation of connected vehicle technology and the study's objectives.

Idea-generation activity Participants engaged in a brainwriting session [67], chosen to ensure equal participation and independent thinking. To stimulate their thinking, several types of visual cues were suggested, including textual forms, colours, symbols, and animation patterns. In the first round, participants wrote their ideas on sticky notes and then shared them verbally with the group. In subsequent rounds, they were asked to build upon others' ideas.

Discussion of biomimicry concepts Participants viewed the video scenarios and discussed the four concepts in sequence. After watching each concept, they responded to specific questions aimed at exploring their perceptions of vehicle connectivity and intention. The focus group discussions concluded with participants reflecting on their overall preferred concept and the extent to which awareness of AV connectivity could enhance their pedestrian crossing experience.

To support transparency and reproducibility, we have made the Miro template used to facilitate the online focus groups publicly available. It is archived for long-term access on the Open Science Framework (OSF): https://osf.io/dfgvb. Additionally, the interactive Miro board can be accessed online: https://tinyurl.com/miro-board-template. These resources may serve as a reference for researchers interested in adapting or extending this study's methodological approach.

5.3 Data collection

Focus group discussions Sessions were video- and audio-recorded. Sticky notes and drawings from Miro boards were archived for subsequent analysis.

Responses to likert questions During the discussion of biomimicry concepts, participants responded to guiding questions, including two 7-point Likert scale items on intention and connectivity. This approach helped researchers identify opinion discrepancies and guide follow-up discussions. The questions included:

(1) From 1 to 7, how easy for you to understand the intention of the vehicles? What are they trying to tell you?
(2) From 1 to 7, to which extent the vehicles appear to be connected to each other? Why?

5.4 Data analysis

The first author transcribed focus group discussions using an AI speech-to-text tool.[6] The transcriptions and written notes on the Miro board were analysed using an inductive thematic analysis technique [8] to identify key themes. The results of focus group

[6] https://otter.ai/

discussions with designers (P1–P8) and non-designers (P9–P16) were not reported separately, as both types of participants shared all identified themes.

We conducted descriptive analyses on the Likert ratings for intention and connectivity communication. However, inferential statistical tests were not applied for two key reasons. First, the Likert-scale responses were designed as a discussion aid rather than for statistical generalisation, a common practice in focus groups [56]. Their primary purpose was to prompt discussion and explore subjective perceptions rather than to produce statistically validated measures. Second, the sample size and recruitment method were structured to maximise diversity of perspectives rather than to support statistical inference. Given the small sample size and non-random selection, statistical tests would have been underpowered and potentially misleading.

6 Results

6.1 Generation of ideas

6.1.1 Preferences for colours and symbols

The participants preferred using colour ($n=7$), symbols ($n=5$), or a combination ($n=4$) to depict the connectivity of AVs. According to P1, colours could be observed from a distance, drawing pedestrians' attention to the vehicles' connection status, while a symbol may provide more explicit information. On the contrary, texts ($n=3$), animations ($n=2$), and sounds ($n=1$) were less considered. Figure 4 shows examples of ideas generated by focus group participants.

6.1.2 Different aspects of connectivity

Connection status The majority of the participants ($n=14$) envisioned the connection status as binary, as reflected in their design ideas. For instance, P10 stated that

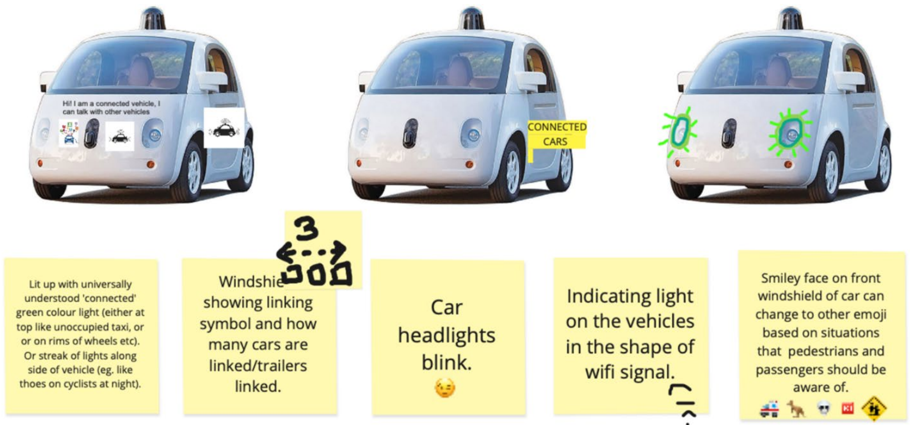


Fig. 4 Examples of ideas that focus group participants generated. Participants could use sticky notes, sketches, or a combination of both to communicate their ideas

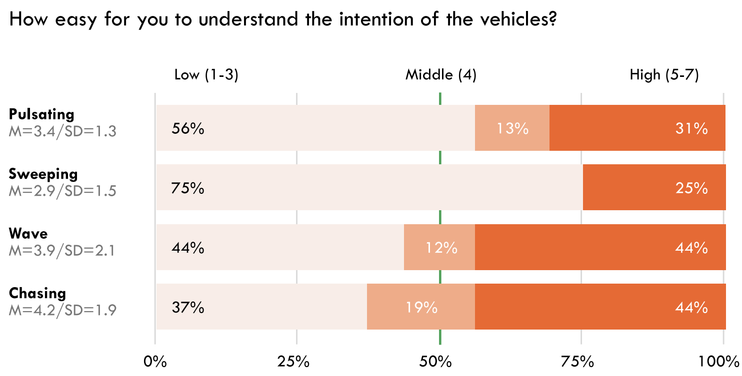


Fig. 5 Ratings of intention communication

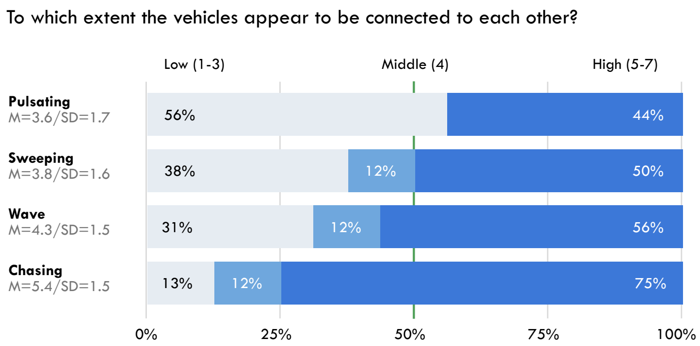


Fig. 6 Ratings of connectivity communication

he was only concerned with a car being connected to and part of the network and, thus, used the *'universally understood green colour light'* to indicate this. However, two participants also considered the quality of the connection. P5 recalled times when her cellphone's Wi-Fi signal had been unavailable and speculated that the vehicle's display *'could be blinking with a different colour'* to indicate a poor connection. In a similar vein, P9 and P10 proposed that different colours of light and Wi-Fi bars, respectively, be used *'in proportion to the strength of the connection.'* Two participants suggested experimenting with low-tech solutions, such as placing a badge on the side doors, arguing that their implementation would be notably simple and might suffice to alert pedestrians to the connection status of AVs.

The number of connected vehicles Three participants expected the external display to include the number of connected vehicles, though the reasons for these expectations were varied. P3 and P8 perceived a clear connection between vehicles bearing the same number, while P9 attributed the number of connections to the strength of the collective perception.

Disconnected vehicles Two participants noted that conveying connectivity could lead to pedestrians overlooking disconnected vehicles and placing themselves in dangerous situations. P6 proposed highlighting disconnected vehicles instead when connected AVs become the more common type of vehicle in traffic situations.

6.2 Discussion of the biomimicry concepts

6.2.1 Intention communication

Figure 5 indicates that the intention ratings for the four design concepts varied, with *Chasing* rated highest (M = 4.2) and receiving the most high scores. *Wave* followed (M = 3.9), showing an even split between high and low scores. *Pulsating* (M = 3.4) and *Sweeping* (M = 2.9) were rated lower, with *Sweeping* predominantly receiving low scores.

6.2.2 Connectivity communication

Figure 6 indicates that the connectivity ratings for all design concepts were above average, with *Chasin*g rated highest (M = 5.4) and receiving the most high scores. *Wave* followed (M = 4.3), showing a majority of high scores. *Pulsating* (M = 3.6) and *Sweeping* (M = 3.8) were rated lower, primarily receiving low or middle scores.

6.2.3 Concept ranking

The concepts in order of preference are as follows: *Wave* ($n = 9$), *Chasing* ($n = 6$), *Pulsating* ($n = 4$), and *Sweeping* ($n = 2$). The total number of votes (21) exceeds the number of participants (16) because five participants could not decide on one option and provided two preferences.

A slight difference existed between the ranking results and the rating outcomes. Although the *Chasing* concept conveyed connectivity most clearly, it ranked second, following the *Wave*. The analysis revealed that participants considered factors beyond clarity in their overall preference, such as aesthetics and the wave pattern's ability to attract attention ($n = 3$). For instance, P15 suggested, *'because connected vehicles are not common nowadays, there must be something special about the design'.*

6.2.4 Key discussion themes

Unclear intention communication Participants struggled to infer intentions from the colour or animation of *Pulsating* and *Sweeping*, relying mainly on movement ($n = 14$). As P8 explained *'the [cyan] colour is confusing because it doesn't match with what we previously know about stopping'*. In contrast, *Wave* was perceived as clearer, as the wave appeared to be sensing and detecting objects ($n = 6$). *Chasing* was seen as indicating crossing directions through its moving lights ($n = 3$).

Synchronised animation: by design or by chance? Many participants concurred that the *'same rhythm,'* ($n = 7$) *'same colour,'* ($n = 3$) and *'same stopping distance'* ($n = 2$)

suggested connectivity. However, these cues were seen as subtle, as the link was not immediately clear without prior knowledge of the technology; as P4 stated, *'someone not doing the previous [brainwriting] exercise would think it was just a cool mod.'* Furthermore, several participants ($n=5$) suspected that the unified rhythm was the result of pure chance. P1, for example, attributed the synchronisation to *'people activating the indicators at the same time.'* Nonetheless, one participant pointed out a distinction between the *Pulsating* and *Sweeping* motions, noting that a synchronised animation pattern in the latter case is more difficult to achieve coincidentally: *'It might be happenstance for the lines to match up perfectly, but for the overall pattern to be in sync was more difficult; therefore, they had to be connected'* (P4).

In indicating connectivity, symbolic visualisation overrode the synchronised animation Concerning the *Wave* concept, participants largely overlooked the identical rhythm of the waves, instead focusing on the potential meanings the waves could convey ($n=9$). When asked about this, P7 acknowledged that she *'noticed they were in sync'* but that she *'just gave it less weight'* because the visualisation explicitly communicated the connectivity, unlike the first two abstract lighting concepts. The *'ripple'* (a term frequently used by the participants to refer to this concept) was stated to resemble a network signal (e.g., Wi-Fi or Bluetooth), Google Nest coverage, and the AirDrop icon. Due to this resemblance, seven participants found it easier to envision connections between the vehicles. Meanwhile, three participants were drawn to the fact that the waves emanated from the vehicle and appeared to overlap. P3 and P4 suggested that connectivity could be more effectively illustrated if the ripples interacted with one another, such as by merging to form a larger wave or *'being disturbed by each other's existence'* (P3).

Continuous visuals indicated connectivity, but scaling it up would be difficult Compared to the first three design concepts based on synchronised animation cycle, the *Chasing* concept, featuring a light segment moving from one vehicle to another, garnered positive feedback for clearly indicating the connectivity between the AVs ($n=12$). Nevertheless, three participants raised concerns about the ability to scale up this concept; for instance, P7 questioned, *'what if there was another row of cars behind?'* P7 also highlighted that observing the movement of the light segment would take some time: *'If there were five cars in a row, it would take five seconds.'* Moreover, the light segment is only visible on one vehicle at a time, causing the remaining eHMIs to appear inactive (P11).

The connectivity aspect was not conveyed in single vehicles The similar behaviour exhibited by a group of vehicles helped to convey connectivity ($n=3$). However, this also led to initial challenges in grasping what was happening upon encountering the first AV, as P16 recounted his experience with the *Pulsating* concept: *'When I see all the cars approaching and pulsating, I understand. However, if it is just one car, I believe it is a modern vehicle; perhaps a new Tesla* has a *glow-in-the-dark paint.'* P15 was also critical of the *Chasing* because *'other cars were necessary to complete the concept'* and the signal could not be seen from the first interaction.

Indications may cause wrong interpretation and distraction Several participants ($n=6$) mentioned how the orchestrated lighting reminded them of light festivals and street celebrations. According to P1, when the design exudes a sense of novelty, a pedestrian's first thought will concern how interesting it is rather than what it is attempting to communicate.

Additionally, car decorations were stated to be common in several cultures ($n = 3$). For example, P1 mentioned that decorating a car was something a *'revhead'* (an Australian term that refers to car enthusiasts) would do, while P4 recalled *'the tuna car culture'* (a reference from the film 'The Fast and the Furious') and the effect of underglow car lights in Mexico. One participant from India suggested that alterations might be made such that people could demonstrate their brotherhood through the similarity of their cars. Moreover, five participants were especially concerned about the possibility of light-based interfaces distracting drivers. P1 thought that the lights in Concepts 2 and 4 were *'almost at the high beam level.'* P2 and P7 agreed on carefully considering the degree of luminance to avoid causing distractions while also being aesthetically pleasing. Two participants mentioned epilepsy concerns, light pollution, and effects on wildlife.

Different views on the usefulness of the proposed design concepts Half of the participants ($n = 8$) stated that connected vehicles could increase their sense of safety during interactions (e.g., crossing the street) due to the vehicles' enhanced perception. P7 mentioned that *'being connected means that the vehicles are smart and [that] they are working together,'* whereas P6 believed that *'on a multi-lane road, it's a reassurance to have cars remind each other even in the situation if one car's sensor fails to work.'* Nonetheless, other participants expressed reservations about needing to know if the vehicles encountered were linked ($n = 8$). P1 did not think that it would alter her pedestrian experience. P10 stated that knowing whether the vehicles would detect pedestrians and yield accordingly was more important for him. Meanwhile, P12 mentioned the issue of a vehicle spreading false information throughout the group.

7 Discussion

7.1 Conveying connectivity between AVs: is it possible?

Considering the participants' connectivity ratings and qualitative comments, the biomimicry concepts evoked associations with connectivity. However, it is critical to note that we had briefed the participants in our study on connected vehicle technology and engaged them in an idea-generating activity prior to the concept evaluation. It was this background knowledge that allowed them to make meaningful associations, suggesting public education campaigns about AVs remain crucial (in line with recommendations from various public opinion surveys [51, 62]). The visual cues function to remind people of the interconnected nature of these vehicles, reinforcing public education efforts. While participants' ratings for connectivity were positive, intention ratings were lower, particularly for *Pulsating* and *Sweeping* concepts. This aligns with existing research on eHMI colour and animation [22], which shows that animation patterns generally have less impact on user understanding compared to colours. Although cyan is recommended in eHMI design for its neutrality [22], it may not be immediately intuitive to users, which could explain the lower intention ratings for these concepts.

Upon examining the ideas generated by participants and contrasting them with our proposed concepts, we noticed key differences in the encoding of the connectivity message. Specifically, participants opted for easily understandable cues and centred their ideas on single vehicles, while we chose a more abstract approach and incorporated multiple vehicles in the representations of connectivity. Based on these findings, we propose a set of design suggestions for seamlessly integrating connectivity aspects into eHMIs:

(1) *Employ intuitive symbolic visualisation:* The effectiveness of design concepts in communicating connectivity depends on the level of abstraction in the coded message. Participants favoured more straightforward visualisations, such as continuous visuals (as seen in *Chasing*) and waves (as seen in *Wave*), over synchronised animation cycle. This preference for easily comprehensible graphical elements was also evident during the brainstorming activity. Most participants suggested that recognisable symbols and distinct colour schemes would be the most efficient means of visually conveying the connected nature of AVs to pedestrians and other road users.
(2) *Ensure balanced novelty:* Incorporating captivating elements into AV external displays can effectively capture pedestrians' attention. However, it is crucial to ensure that the novelty does not detract from the clarity of the intended message, such as the AV's intent to yield or the connectivity among AVs. Even though the novelty effects might wear off over time, it is essential for eHMIs to be perceived as functional features rather than merely decorative elements.
(3) *Communicate single-vehicle connectivity:* Our proposed design concepts primarily conveyed connectivity between AVs using multiple eHMIs. However, participants anticipated that connectivity information should also be accessible for single vehicles (e.g., using a designated light or badge). This consideration is particularly relevant when connected vehicle technology encompasses more than just inter-vehicular data exchange, extending to communication with roadside infrastructures and pedestrians' devices [7]. Informing pedestrians of connectivity capabilities may help build trust in AV technology by showcasing the advanced features and intelligence of these vehicles.
(4) *Consider practical implementation:* Balancing the efficacy of design concepts in conveying connectivity with practical implementation is vital. For example, while synchronised animation cycle was occasionally perceived as coincidental, its implementation may only require standardising animation patterns and utilising computer chips to sync up animation cycle. Conversely, although the *Chasing* concept was highly effective in conveying connectivity, its real-world implementation may be too complex to be practical or scalable.

7.2 Conveying connectivity between AVs: is it desirable?

Our design exploration was driven by the need to help pedestrians understand how AVs function as a networked system, rather than as isolated units. The goal was to develop visual cues that communicate not only the intents of individual AVs but also their connectivity and coordinated actions. Focus group discussions revealed that while participants did not view connectivity as essential as intent communication, half believed that visualising connectivity could improve their perception of safety. Knowing that AVs coordinate with one another and share sensor data was seen as reassuring, particularly in scenarios where one vehicle's sensors might fail. According to a study on AVs' potential to reduce pedestrian fatalities, the ability of advanced sensors to detect pedestrians ahead of collisions varied widely, from less than 30% to over 90% [16]. In this context, connected AVs offer enhanced safety through data sharing. Visualising connectivity highlights this 'teamwork' capability; therefore, future research can systematically study the impact of such visualisations on pedestrians' sense of safety and potential consequences. For instance, some pedestrians may become overconfident in AV safety and engage in riskier behaviours [39], assuming the vehicles will always detect them and respond accordingly.

While this study focuses on exploring ways to visualise AV connectivity, future work could investigate whether visualising connectivity between AVs supports acceptance and trust in interconnected eHMIs. Since this approach has faced challenges due to pedestrians' limited awareness of connected vehicle technology [15], visualising connectivity could help pedestrians interpret the behaviour of multiple AVs more confidently by making it clear that when one vehicle stops, others are likely to follow. We envision a dual-layer communication system, where AV connectivity is conveyed as a secondary message, while crossing intent remains the primary message. However, the effectiveness of layering connectivity cues onto existing eHMIs must be systematically tested. Integrating connectivity information alongside intent signals may either reinforce pedestrian understanding or introduce ambiguity, particularly in multi-vehicle environments where pedestrians must interpret multiple cues in real-time. Does adding connectivity information enhance their ability to anticipate AV behaviour, or does it introduce cognitive overload? Future studies should evaluate the effectiveness of this dual-layer approach in multi-vehicle scenarios through controlled experiments.

7.3 Towards interconnected external human–machine interfaces

Building on our design exploration of eHMIs that convey connectivity, we propose two potential research avenues related to interconnected eHMIs. Unlike traditional eHMIs, which focus solely on an individual vehicle's operational state, interconnected eHMIs consider other vehicles and a broader range of traffic conditions. As a result, these systems could be designed to enable safer and more intuitive communication with pedestrians.

(1) *Communicating adaptively:* Signal strength emerged as a major concern for several focus group participants, echoing findings by Tran et al. [65], where pedestrians expressed apprehensions about possible failures such as disconnections and signal transmission delays. In light of this, we suggest that eHMIs, particularly interconnected ones, should be transparent about their limitations, much like how autonomous driving systems communicate their confidence levels to drivers [55]. The external interface could adapt its messaging according to the certainty of a traffic situation. For example, if a vehicle is unsure about the safety of other lanes (e.g., due to poor connection quality), it might display a message like 'cross with caution' rather than 'cross'. This approach addresses safety concerns related to current eHMIs, which typically provide crossing information for only the lane directly ahead, rather than all lanes a pedestrian must cross [43]. Moreover, this adaptive messaging could counterbalance overtrust in eHMIs by making uncertainties transparent and ensure their viability in mixed traffic that include disconnected or legacy vehicles. A similar adaptive approach has been implemented in auditory interconnected eHMIs, where the vehicle shortens the message to I'm stopping' (instead of I'm stopping, you can cross') to avoid instructing pedestrians to cross in potentially unsafe situations.

(2) *Communicating intuitively:* User studies have shown that pedestrians prefer clear signals to cross [65] and benefit from the intuitiveness of conventional colours [3, 22], a conclusion supported by our qualitative analysis. However, avoiding explicit instructions is a recommended practice in eHMI design [1, 30], as directing pedestrians to cross can raise liability issues and ethical concerns in the case of collisions [21, 34].

As such, traffic light colours are generally discouraged due to their association with instructions rather than announcements [22]. These considerations are particularly relevant when AVs are unable to fully determine the intentions of other road users. However, if AVs can achieve collective situational awareness through connectivity, it may be worth reevaluating the use of instructive or advisory elements in eHMI design.

7.4 Limitations and future work

This study focused solely on visual communication, potentially overlooking other sensory modalities (e.g., auditory signals) that could offer a more holistic approach to conveying connectivity. While the proposed design concepts built upon existing eHMIs, there were minor discrepancies in the animations due to a lack of access to original source files.

Specifically, the LED light band was slightly smaller, and the sweeping motion appeared less fluid than in the Bumper eHMI created by Dey et al. [24]. Another limitation of the prototypes was the glowing effect of the LED lights in the night scene, created by the Unity Bloom filter. With no standard brightness range available, we implemented a value we deemed appropriate, though several participants found the effect overly bright.

While we initially determined our sample size based on qualitative research norms and data saturation, we did not explicitly apply the concept of information power during the study design phase. Upon reflection, our study aligns with key aspects of information power [47], as it had a relatively narrow aim—exploring visual representations of AV connectivity—and involved a specific participant pool composed of design experts and non-designers with relevant backgrounds. These factors suggest that our sample size was appropriate for generating meaningful insights. HoweveVr, we acknowledge that integrating information power earlier in the research design process could further strengthen qualitative inquiry, particularly in design-focused HMI studies, which remain underexplored in AV research [25]. We recommend that future research explicitly consider information power when determining sample size, ensuring a more systematic approach to balancing study aims, participant specificity, and data richness.

The online focus group setting proved efficient and fostered in-depth discussions, but potential issues outside our control—such as internet instability and environmental distractions—might have affected participants' experiences. Additionally, while the animated video prototypes worked well in an online environment, they lacked interactivity and immersion, limiting insights into pedestrians' behavioural and emotional responses. Future work will focus on refining the design concepts and conducting experiments in fully immersive virtual reality to assess the effect of visualised connectivity on AV–pedestrian interactions.

8 Conclusion

This paper has presented a design exploration focused on developing visual design concepts to convey connectivity between AVs. While several design elements successfully suggested vehicle connectivity, meaningful associations from pedestrians relied on prior knowledge of connected vehicle technology. Additionally, visualising AV connectivity shows potential for enhancing pedestrians' perceived safety. We hope this exploration fosters continued discussions on designing eHMIs that promote greater system transparency and encourages further research into interconnected eHMIs as a solution for scalability challenges.

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Authors' contributions All authors contributed to the study's conception. Tram Thi Minh Tran developed the interface concept designs, animated video prototypes, and study materials. Tram Thi Minh Tran and Yiyuan Wang facilitated the focus group discussions. Data collection and analysis were conducted by Tram Thi Minh Tran and Yiyuan Wang. The manuscript was primarily written by Tram Thi Minh Tran. All authors reviewed and approved the final manuscript.

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Data availability Due to ethical restrictions outlined by the University of Sydney Human Research Ethics Committee (HREC) and the need to protect participant privacy, the dataset is not publicly available. Researchers interested in accessing the data within the ethical guidelines may contact the corresponding author to discuss potential arrangements.

Declarations

Competing interests The authors declare no competing interest.

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