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On face value: a ghost driver field study investigating interactions between pedestrians and a driverless vehicle with anthropomorphic displays

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ABSTRACT

In a novel, on-road study, using a 'Ghost Driver' to emulate an automated vehicle (AV), we captured over 10 hours of video (n = 520) and 64 survey responses documenting the behaviour and attitudes of pedestrians in response to the AV. Three prototype external human-machine interfaces (eHMIs) described the AV's behaviour, awareness and intention using elements of anthropomorphism: High (human face), Low (car motif), Abstract (partial representation of human features that lacked precise visual reference); these were evaluated against a (no eHMI) baseline. Despite many pedestrians reporting that they still relied on vehicular cues to negotiate their crossing, there was a desire/expectation expressed for explicit communication with future AVs. High and Low anthropomorphism eHMIs received the most positive responses for clarity, confidence and trust, with High also attracting significantly more/longer glances and the highest preference rating. In contrast, Abstract was considered least clear and subsequently invited the lowest confidence and trust ratings.

Practitioner summary: Utilising the 'Ghost Driver' methodology to emulate an automated vehicle, we evaluated prototype external human-machine interfaces designed to replace absent pedestrian-driver communication. Video and survey data support the use of explicit communication to help pedestrians negotiate safe crossing and demonstrate the value of employing anthropomorphism in the design of interfaces.

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Ghost Driver; field study; external human-machine interface; pedestrian; anthropomorphism

Introduction

In future, mixed traffic environments, automated vehicles (AVs) will need to interact safely with other 'non-automated', and potentially more vulnerable, road users, such as pedestrians, especially in situations where they occupy the same road space (e.g. a pedestrian wishes to cross the road). It is therefore important that all road users have a good understanding of the behaviour and intentions of AVs, especially in the absence of an accountable human driver. Currently, humans use a variety of cues (implicit and explicit) to interpret the intention and behaviour of vehicles and subsequently plan their own actions accordingly. These cues may include approach speed and deceleration profile of a vehicle, as well as eye contact and gestures exchanged with a driver or a rider, although it has been reported that, in current traffic situations, vulnerable road users such as pedestrians tend to rely on the former, implicit cues, rather than explicit communication to make their judgements (Lee et al. 2021; Merat et al. 2019). Nevertheless, formative, underlying principles of AV control algorithms tend to focus on collision avoidance (Urmson et al. 2008), rather than communicating the AV's behaviour and intention to other road users. The absence or misrepresentation of implicit or explicit cues, by design or otherwise, means that the behaviour of an AV may be either unknown or potentially misinterpreted by other road users, and this may hinder the safe and successful integration of AVs within future mixed traffic environments. A proposed solution is to provide explicit communication using an external human-machine interface (or eHMI), which can replace explicit cues that would hitherto have been provided by the driver, as well as potentially offering additional information about the vehicle's behaviour and intentions. Several novel concepts have subsequently been proposed, such as dynamic lighting effects and transient crossings projected on the road ahead of the vehicle (see: Dey et al. 2020). In addition, anthropomorphism (i.e. human attributes or mannerisms) often features in eHMI designs, and

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indeed in the design of AVs more generally, where it has been shown to improve understanding, acceptance and trust (Zhou et al. 2022). Nevertheless, many of the conceptual eHMI designs lack theoretical basis or empirical evaluation, and it is unclear whether any potential benefits offered by anthropomorphic eHMIs would translate to real-world settings. The current study therefore aims to address these research gaps by evaluating explicit communication from an AV to pedestrians, regarding its awareness, behaviour and intention, using theoretically-grounded, anthropomorphic eHMI designs in a naturalistic, on-road context.

Current pedestrian-vehicle communication and negotiation

Interpreting intention and coordinating planned action is especially important in situations where infrastructure-based guidance, such as traffic lights and marked crossings, are absent. However, it has also been highlighted that road users routinely use implicit and explicit cues to interpret intention and behaviour even in situations where the 'rules-of-the-road' are clearly defined and generally well-understood, for example, at a marked 'zebra' crossing (Merat et al. 2019). Nevertheless, specific behaviours (both implicit and explicit) may differ depending on cultural and social norms and expectations. Whilst there has been some recognition that in many situations the predominant cues processed by a pedestrian (in both situations above) are the vehicle's speed and distance from the crossing point (i.e. implicit cues, Dey and Terken 2017), it is also clear that explicit pedestrian-driver social negotiations are still considered important to overall traffic safety, especially in low-speed crossing scenarios in complex urban settings (Moore et al. 2019). These may include gestures such as hand movements, flashing lights or indicator signals (Sucha, Dostal, and Risser 2017) and eye contact (Guéguen, Meineri, and Eyssartier 2015).

Explicit pedestrian-vehicle communication and negotiation ultimately aims to establish a mutual understanding of perception (have you seen me? I have seen you), approach intent (will you give way? I am giving way here/to you) and leave intent (you can set off again; I am about to move my vehicle) etc. (Merat et al. 2019). The lack of possible eye contact in the absence of an accountable human driver in future AVs is often used as an argument for some form of external communication (and indeed, is evidently the inspiration behind many of the more outlandish concepts). Nevertheless, findings from observational studies in current traffic settings on this specific point are mixed, with some authors highlighting the importance of eye contact in pedestrian-vehicle interactions (Habibovic et al. 2018), whereas others report the relative absence of eye contact from roadside negotiations (Lee et al. 2021; Moore et al. 2019).

Regardless of the precise mechanism, it is expected that some form of explicit communication from an AV to pedestrians and other vulnerable road users will be important to secure underlying confidence and trust in AVs, in addition to the aforementioned safety benefits, particularly during the initial stages following the widescale introduction of such vehicles (Mahadevan, Somanath, and Sharlin 2018; Moore et al. 2019). A number of eHMI designs have subsequently been proposed that utilise lights, displays, and/or projections to communicate with other road users (see: Zhou et al. 2022; Dey et al. 2020). However, deciding precisely what to present and how to present it remains a challenge.

Design challenges

Message content ('what to present')

There has been some debate regarding whether an eHMI should encourage other road users to act or simply to communicate the host vehicle's intent and let the other road user decide, in other words whether the message should be *egocentric* or *allocentric* (see: Eisma et al. 2021). The former is targeted directly at the pedestrian, or another road user, and invites them to take a specific course of action (e.g. 'you may cross now'), whereas the latter must be interpreted by the pedestrian and is provided from the AV's perspective (e.g. 'I am approaching the crossing and I have seen you'). The general consensus appears to be that an AV should avoid explicitly instructing people to act, but rather provide allocentric messages, that can be interpreted from the other road user's perspective (Andersson et al. 2017). This view is supported by a number of authors (e.g. Habibovic et al. 2018; Strömberg) and also aligns with legislation and official guidance in many countries. For example, in the UK, drivers are told that they 'must not wave, flash their lights or use their horn to invite pedestrians across' (UK Highway code Rule 195 Zebra and parallel crossings 2023). Others have highlighted the requirement of an AV to also communicate its driving mode (Yang, Han, and Park 2017) and its awareness (Mahadevan, Somanath, and Sharlin 2018).

Anthropomorphism ('how to present it')

A common feature in eHMI designs is the inclusion of 'human' elements or mannerisms (so-called 'anthropomorphism'). In technology, anthropomorphism has been applied to designs to provide a practical means of solving a specific problem, to create an emotional connection between the technology and its user, or to help explain interactions with a complex system, such as automation (DiSalvo and Gemperle 2003). Studies have already shown that using anthropomorphism in the design of AVs can aid understanding, acceptance and trust (Zhou et al. 2022). For example, by giving an AV a human name, gender and humanlike voice, so that it appeared that vehicle occupants were interacting with a human companion rather than a machine, they were less likely to allocate blame to the vehicle following an accident, compared with an AV absent of these features; occupants also reported higher levels of trust in the former (Waytz, Heafner, and Epley 2014). Similarly, the provision of an in-vehicle HMI offering humanlike conversational interaction in an AV-pod driving experience enhanced the ratings of trust and perceived intelligence and capability of the AV, compared to the same AV-pod provided with a graphical user interface, and the overall experience was perceived as more pleasurable (Ruijten, Terken, and Chandramouli 2018; Large et al. 2019). Kaleefathullah et al. (2022) go further to suggest that anthropomorphism is one of four key features to enhance pedestrian-AV trust (the other three being: novelty, transparency and mode of communication).

Much of the theoretical foundation for the application of anthropomorphism in technology design has occurred in the field of human-robot interaction, where there is a desire for robots to be perceived as more friendly, competent, and trustworthy (Waytz, Cacioppo, and Epley 2010). Thus, anthropomorphism is commonly manifested as a human face or eyes, which can convey emotion and intent in ways that users can easily interpret, even when the face appears on technology (Reeves and Nass 1996). It is noted that there are significant cultural differences and social nuances in users' desire for and affinity with anthropomorphism, particularly where it has been applied to cars and technology, and receptivity towards eyes and faces on cars, in particular, appears to vary significantly. Indeed, critics tend to dismiss the addition of eyes and/or a face as inappropriate, 'kitsch' (DiSalvo and Gemperle 2003) or even dangerous, and warn against the uncanny valley effect (Faas, Mathis, and Baumann 2020; Löcken, Golling, and Riener 2019) if the vehicle subsequently becomes too humanlike in its appearance or behaviour. The use of eyes within pedestrian-AV interactions is also often criticised in its ability to detect and communicate with more than one pedestrian at a time; however, the same criticism is seldom cast upon the human driver whom it intends to replace.

Nevertheless, eyes and/or a face (and anthropomorphism, more generally) commonly feature in proposed eHMI concepts, where these features are used to convey the vehicles' intentions to pedestrians. Examples include the eye concept (by Jaguar Land Rover), the smiling car concept (by Semcon), and the hand gesture concept (Zileli, Boyd Davis, and Wu 2019; Mahadevan, Somanath, and Sharlin 2018). In the case of the smiling car concept, a smile appears on the front eHMI to confirm the AV's intention to give the right-of-way to pedestrians. It was further anticipated by the designers of this particular eHMI that a smiling face would indicate the AV was friendly, and as a result, pedestrians would feel more comfortable when interacting with it (Deb, Strawderman, and Carruth 2018).

Methodological approach: Ghost Driver

The majority of empirical research exploring pedestrians' behaviour in response to AVs has used immersive virtual reality (VR) as an experimental means to compare different communication strategies and technologies and to understand how pedestrians might respond to an AV in highly defined scenarios. These studies commonly focus on the same use-case, namely when one pedestrian (the participant) is aiming to cross a single-carriageway road at either a managed or non-managed crossing and is required to interact with a single approaching vehicle (e.g., De Clercq et al. 2019). This focus is understandable, partly as AVs do not exist on roads presently, but also because VR, as an experimental approach, can provide high control, minimise confounding variables, and provide precise behavioural data, such as specific gaze points and head rotations, which can be difficult to extract from naturalistic methods (Feng, Duives, and Hoogendoorn 2022). However, Schneider and Bengler (2020) warn that the successful application of VR as a methodological approach does not guarantee the validity of the results. Moreover, in the context of a pedestrian crossing the road, there are many 'real-world' motivational factors that may influence a pedestrian's decision regarding when it is safe to do so, that are unlikely to emerge in a VR study (Moore et al. 2019). Thus, it has been cautioned that although certain elements may perform well in VR evaluations (and indeed, may feature highly in the plethora of proposed eHMI concepts), it does not necessarily follow that these are the most effective and accessible means of communication with vulnerable road users in real-world crossing scenarios.

In contrast, there have been several high-profile studies (e.g. Rothenbücher et al., 2016; Currano et al.

2018; Fuest, Schmidt, and Bengler 2020) which have employed a Wizard-of-Oz (WoZ) approach (Dahlbäck, Jönsson, and Ahrenberg 1993) to simulate an AV on the road, including several studies specifically aiming to evaluate eHMIs (e.g. Dey et al. 2021; Faas, Mathis, and Baumann 2020; Hensch et al. 2020). In these studies, pedestrians' expectations of the vehicle are 'breached' (Weiss et al. 2008) in that the driver is hidden from view using a bespoke seat cover suit, often affectionately referred to as the 'Ghost Driver' method (Rothenbücher et al., 2016). Such an approach arguably provides higher ecological validity than VR, enabling researchers to understand how pedestrians might naturally behave when faced with a convincing 'self-driving' vehicle in genuine, real-world, mixed traffic scenarios, and has further scope to reveal unexpected behaviours that were not envisaged or could not be controlled as part of a laboratory-based VR study. This might include the influence of group and social dynamics and behaviours when several pedestrians are wishing to cross the road, personal motivational factors that may affect a pedestrian's attitude towards risk in a specific real-world situation, or obscuration of the eHMI due to unexpected or vexatious behaviour of other road users, inclement weather conditions etc.

Utilising 'real-world' methods to study pedestrian-AV interactions has indeed revealed new and unexpected behaviours in response to the AV, such as aggression and 'griefing' towards the vehicle (Moore et al. 2020), and even some incidents of pedestrians 'playing' with the AV to test its sensor capabilities (Currano et al. 2018). In real-world studies, pedestrians have also expressed difficulty interpreting the behaviour of the vehicle (Fuest, Schmidt, and Bengler 2020), and reported feeling less safe, and 'doubtful' about their interaction with the AV (with some pedestrians notably choosing to change their path and cross behind the vehicle) (Palmeiro et al. 2018). However, this research has primarily occurred in the US/North America. Consequently, there is a lack of understanding regarding how pedestrians and other road users might behave in response to an AV in other cultural contexts, where factors such as road infrastructure, social norms, risk perception, prevailing trust relationships, and so on, may differ.

Overview of study

The current study utilises the aforementioned WoZ ghost driver method (based on the seminal approach taken by Rothenbücher et al., 2016) to emulate a driverless vehicle. Three eHMI prototype designs were created for the study. The designs were informed by the literature and employed varying degrees of anthropomorphism (notionally referred to as: high, low and abstract), with the aim of also evaluating how anthropomorphism affects the information relayed by the eHMI and pedestrians' attitudes towards the AV (i.e. their trust, confidence, etc.).

Designing and implementing the eHMIs

Background and motivation

The three eHMIs under evaluation were intended as exemplar designs informed and inspired by the literature to showcase different design choices and applications of anthropomorphism, as well as different physical implementations and configurations on the vehicle itself. However, these were not controlled variables, in the sense that we were not aiming to explore how the perception of anthropomorphism could be varied by subtly changing the shape or behaviour of eyes, for example, but rather if and how pedestrians' behaviour differed in response to an overtly anthropomorphic eHMI (as defined by the literature) compared to more functional, mechanistic alternatives.

The application of anthropomorphism within our eHMI designs centres largely around the human face and the number and fidelity of facial features. Faces and eyes already feature in a number of conceptual designs for eHMIs (see: Dey et al. 2020). This is understandable as humans possess an intrinsic ability to recognise faces (Gauthier et al. 2003), and from early childhood learn to assign emotional and social significance to the eyes and face, and develop visual language skills that are especially sensitive to eye contact, head orientation, eyebrow motion and mouth shape (Ventrella 2011). When applied to a non-human entity, facial features and mannerisms can thus enhance the perception of its humanness. In the context of human-robot interaction (where much of the seminal research on anthropomorphism resides), DiSalvo et al. (2002) found that the *presence* of certain facial features (eyes, eyebrows, mouth) and the *total number* of these features significantly influenced how humanlike users perceived robot heads to be. Nevertheless, they warn not to adopt full human facial features and dimensions to avoid potential uncanny valley effects, whereby the emotional response to an object declines as the object approaches near-human resemblance (Mori, MacDorman, and Kageki 2012; Reichardt 1978).

DiSalvo et al. (2002) further conjectured that the humanness of a robot is defined not only by its physical form but by its interactions through expression, communication and behaviour, and thus recommend that in situations where it is not possible or feasible to design actual facial features (or indeed, an 'head' to host these), providing suggestions of or affordances for those features is sufficient to create an overall perception of humanness, assuming that is the ambition (DiSalvo et al. 2002). This also allows for the host technology to retain a reasonable degree of familiarity with its intended functional state, allowing users to perceive the non-human qualities, emotional limitations and the purpose it serves – a sentiment also shared by Mori, MacDorman, and Kageki (2012). With this in mind, DiSalvo et al. (2002) provide design recommendations to manipulate the humanness of an artificial face while maintaining the product's quintessential form and function (see: DiSalvo et al. 2002 for further information). We have used this guidance to inform our three eHMI designs, each of which features varying degrees of anthropomorphism. For the purpose of this paper, we refer to these as 'High' (overt anthropomorphism, with clearly discernible facial features and humanistic language), 'Abstract' (implied anthropomorphism, with a partial representation of human features, specifically a human eye, but lacking precise visual reference) and 'Low' (primarily using functional or mechanistic car-centric language and imagery to communicate with pedestrians). Further details of each design are provided below.

High anthropomorphism (HA)

The High Anthropomorphism eHMI (HA) utilised both an LED strip located above the windscreen and an LED matrix on the front of the vehicle to create our most 'humanlike' interface. The matrix displayed elements of a face/persona (affectionately named 'Hathaway', after the titular character in the anime film[1]), with 'complexity and detail in the eyes', 'multiple features' that 'dominated the face' and a face that was 'wider than it was tall' (in line with four of the recommendations made by DiSalvo et al. 2002). Hathaway's mouth, eyebrows, eyes and pupils adopted natural human behaviours, for example, the eyes moved side-to-side to look/scan and the eyebrows inclined to draw attention to the eyes and the direction of their gaze. If a pedestrian waiting to cross the road was detected, the eyes paused at the appropriate side of the vehicle, and the face then smiled and 'spoke' via written, human language to inform the pedestrian 'I am giving way' (presented in a speech bubble/balloon to suggest that the car had spoken this message). The use of the first-person point of view and active voice specifically highlighted the fact that the vehicle was referring to itself in the first person and thus identified itself as human. If pedestrians were on both sides of the road, the eyes and spoken text were presented on each side, in turn. The LED strip remained fully illuminated throughout to indicate that the vehicle was in autonomous mode.

Abstract anthropomorphism (AA)

The Abstract Anthropomorphism eHMI (AA) utilised the LED strip located above the windscreen. The design used a 'mono-eye' concept that mimicked the pupillary response of an eye and took inspiration from the animation 'Gundam'[2] and the television series 'Knight Rider'[3]. The 'mono-eye' moved from side-to-side to represent looking/scanning. If a pedestrian waiting to cross the road was detected, the pupil constricted to indicate that its attention had been drawn, and subsequently blinked. The blinking was intended as an implicit cue that the vehicle was giving way. The AA design is thus a simpler and more abstract application of anthropomorphism, compared to HA, and makes a *suggestion* of an eye rather than an explicit and precise visual representation (as recommended by DiSalvo et al. 2002).

Low anthropomorphism (LA)

The low anthropomorphic eHMI (LA) utilised both the LED strip and the LED matrix and minimised the use of anthropomorphism in its design. When a pedestrian was detected waiting to cross the road, the matrix drew the pedestrian's attention by displaying an image of a car along with the message 'giving way' (i.e. 'car is giving way' provided as a statement of fact). In addition, the mono-eye was displayed on the LED-strip, but this was primarily to indicate on which side of the road the pedestrian had been noted. Using the car image in addition to functional, mechanistic language, which specifically avoided the use of the first-person point of view to reduce any implied humanness, also reinforced the technology's intended form and function as a vehicle (as recommended by DiSalvo et al. 2002) and minimised the likelihood of straying into the uncanny valley (Mori, MacDorman, and Kageki 2012). In addition, maintaining the mono-eye, but using it for a more functional purpose, kept a subtle anthropomorphic element to the design.

Implementation

All three designs were prototyped using an individually addressable RGB-LED matrix and RGB-LED strip attached to the outside of the vehicle (on the front of the bonnet and top of the windscreen, respectively), which were controlled by an Arduino Mega board (Figures 1 and 2). A 'blue-green' colour was selected for all elements, as recommended within the ISO standard currently under review (see: ISO 2024). Brightness was set at '200' (as defined by the Arduino analogWrite() LED function), which equated to approximately 1255 lumens, or 'high' brightness, to improve the visibility of each design.

For each design, five states were created: autonomous mode, scanning, giving way (pedestrian/s on right), giving way (pedestrian/s on left) and giving way (pedestrian/s on both sides of road) (see Table 1 for further details). These were intended to communicate the AV's driving mode, awareness and intent, and specifically avoided inviting people to cross the road, in line with recommendations (Yang, Han, and Park 2017; Mahadevan, Somanath, and Sharlin 2018; Andersson et al. 2017) and official guidance (UK Highway code Rule 195 Zebra and parallel crossings 2023). The modes were presented sequentially and in numerically ascending order for each interaction and this was consistent for each design (HA, AA, LA). For example, M1 autonomous mode was displayed during routine driving. As the vehicle approached a crossing, M2 scanning mode was displayed. If a pedestrian was observed on the right, M4-R giving way (right) mode was displayed. This corresponded with the onset of braking/deceleration to ensure that the eHMI states matched the vehicle kinematics (i.e. implicit cues). When the pedestrian/s had crossed, and no further pedestrians were waiting or nearby, M2 scanning mode was reselected before driving away. All changes were made manually by a researcher sitting in the rear of the car.

Method

To capture naturalistic responses to the different eHMIs, a 'ghost driver' study was conducted (inspired by Rothenbücher et al., 2016), in which the driver of a manual vehicle wore a bespoke 'seat costume' that was designed to enable the driver to maintain safe control of the vehicle, whilst ensuring that they could not be seen by a passing pedestrian glancing into the vehicle. A second researcher sat in the back of the vehicle; their role was to activate the different eHMI states and to support the driver. The second researcher remained in view. It was anticipated that anybody seeing the second researcher would think they were a passenger in the car.

Seat costume

The intention was to create the impression that the study vehicle (in this case, a Nissan Leaf EV) was driving autonomously and thus deprive pedestrians of any chance of interacting with a human in the car. To accomplish this, we designed and fabricated a 'seat costume' to be worn by the driver (Figure 3). The basic

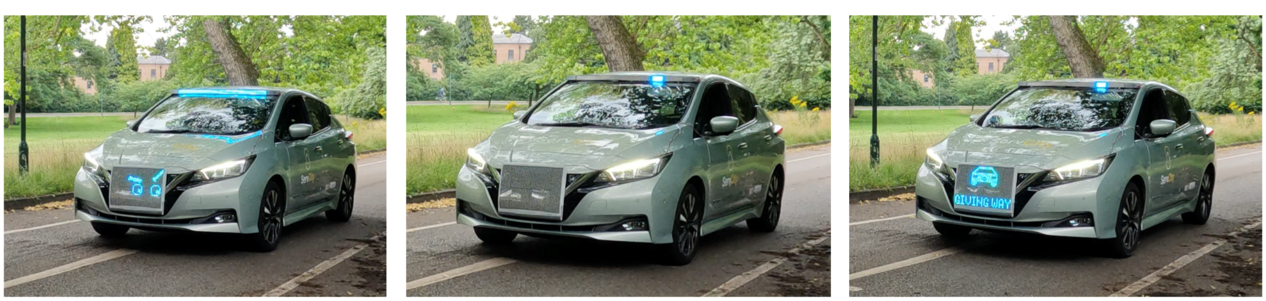

Figure 1. High (L), Abstract and Low (R) eHMI designs.

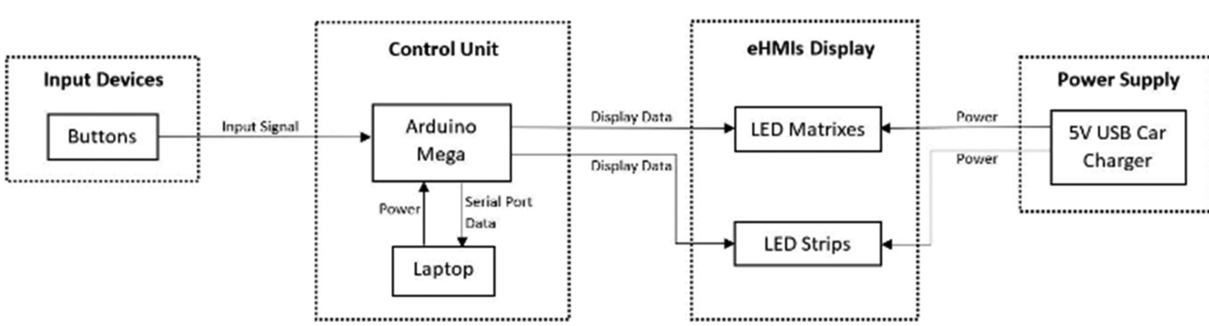

Figure 2. Block diagram of the eHMI system implementation.

Table 1. Information displayed on RBG-LED matrix and strip for each condition/mode.

Mode	Message conveyed	High anthropomorphism		Abstract anthropomorphism		Low anthropomorphism		No-eHMI
		LED-matrix	LED-strip	LED-matrix	LED-strip	LED-matrix	LED-strip	Matrix + Strip
M1 – Autonomous mode	I'm in autonomous mode	Eyes looking from left to right	Fully lit	Blank	Fully lit	Blank	Fully lit	Blank
M2 – Scanning mode	I'm checking/scanning	Eyes looking from left to right	Fully lit	Blank	Mono-eye scanning	Blank	Mono-eye scanning	Blank
M3-L – Giving Way (Yielding) mode (left)	I've seen you waiting to cross on the left, I'm giving way	Eyes look to both sides, a smile appears and text to left stating 'I'm giving way'	Mono eye scanning and blinking on left	Blank	Mono eye scanning and blinking on left	Displays message: '[Vehicle icon] Giving Way'	Mono eye scanning and blinking on left	Blank
M4-R – Giving Way (Yielding) mode (right)	I've seen you waiting to cross on the right, I'm giving way	Eyes look to both sides, a smile appears and text to right stating 'I'm giving way'	Mono eye scanning and blinking on right	Blank	Mono eye scanning and blinking on right	Displays message: '[Vehicle icon] Giving Way'	Mono eye scanning and blinking on right	Blank
M5-LR – Giving Way (Yielding) mode (both sides)	I've seen you waiting to cross on both sides, I'm giving way	Eyes look to both sides, a smile appears and text alternates to left and right stating 'I'm giving way'	Mono eye scanning and blinking, alternates to left and right	Blank	Mono eye scanning and blinking, alternates to left and right	Displays message: '[Vehicle icon] Giving Way'	Mono eye scanning and blinking, alternates to left and right	Blank

shape of a seat was created from reinforced cardboard and covered by original seat material, with the main body covering the driver's torso and the headrest covering their head. To ensure that the driver could see (forward and peripherally), a slot was cut in the headrest section and covered with semi-transparent, black fabric. The sides of the seat costume were fashioned to provide free access for the driver's arms and enable them to manoeuvre the vehicle using the lower section of the steering wheel; this also ensured that their arms remained below the window. The driver wore black attire and black gloves, and fitted their safety belt before applying the seat costume. In addition to the external LED displays under evaluation, the vehicle had ServCity[4] project branding identifying project partners, but nothing extra was added to the vehicle to specifically suggest that it was driverless (or intended to appear so).

Location and route

The vehicle was driven around the extensive University of Nottingham campus, following a predetermined, circular route that included three demarcated 'zebra' crossings and one unmarked (but commonly used) crossing point. Each crossing occurred in the vicinity of a junction. Part of the route formed a common path between lecture theatres and the student facilities building and so was highly frequented by pedestrians, especially between lectures and during lunch. Prior to running the study, a nearby 'waiting' area was selected, with low pedestrian traffic (a carpark). The waiting area was used to make any physical modifications to the vehicle, for example, installing the eHMI (and the driver's seat costume) at the start of the day and making any changes between conditions.

Driver training and vehicle setup

Prior to conducting the study, the driver and the second researcher drove around the route several times without the seat suit to familiarise themselves with the location and to determine precisely when to activate or change between different eHMI states. The driver then put on the seat costume and drove the car with the support of the second researcher around a different, quieter area of the campus (notably absent of pedestrians) several times until they were comfortable wearing it while driving. Finally, the driver practised driving on the selected route wearing the seat costume. Next, the LED-strip and LED-matrix were attached to the vehicle and the sequences of states practised while the vehicle remained in the waiting

Figure 3. Driver hidden in front seat costume.

area. When both the driver and the second researcher were comfortable with the setup, and their roles within it, the study could begin. The vehicle was driven using a cautious, defensive driving style (see: Faas, Mathis, and Baumann 2020; Hawkins 2018) and complied with all regulations (e.g. the 20 mph speed limit on campus); braking and acceleration were applied 'gently'. The vehicle 'gave way' to all pedestrians wishing to cross the road. This driving style was replicated across conditions, although it is noted that vehicular behaviour may have varied subtly on each approach to a crossing (depending on the precise location and trajectory of pedestrians wishing to cross); vehicle kinematic data were not specifically captured. The driver (hidden in the front seat) and the second researcher (sat in the back of the vehicle) were in constant verbal communication during the study to ensure that all pedestrians had been observed, and any issues could be resolved promptly.

Study protocol

Data were collected at different times and on three different days of a week to ensure that there was a representative sample of pedestrians. The vehicle travelled the same distance (i.e., same number of circuits of the route) while displaying each of the three eHMI designs. A fourth, baseline condition (with no eHMIs displayed – 'NO') was also evaluated, with all 4 conditions (HA, AA, LA and NO) evaluated on each occasion. All testing occurred on dry and bright days and during daylight hours, typically late morning or early afternoon. The current state of the eHMI (autonomous driving, scanning, giving way/yielding etc.) was determined by the second researcher located in the rear of the vehicle in response to the behaviour and proximity of any observable pedestrians in the vicinity of the vehicle as it approached each crossing, as well as any other pedestrians appearing to wish to cross the road outside of the four specified crossing zones. Between crossings, the relevant autonomous driving/scanning mode was displayed. The different modes were activated using a custom-made Arduino Mega board and push-button controls, which changed the active state with immediate effect.

Analysis and measures

In total, approximately 10 hours of videographic data were captured using GoPro cameras and a dashcam (front and rear) located within the vehicle, which recorded pedestrians' responses to and behaviour around the 'driverless' vehicle and in response to the different eHMIs. Episodes of videographic data pertaining to the four crossings were extracted and coded. This resulted in 130 mins of coded data, approximating to 32.5 mins per eHMI; in total, the behaviour of 520 pedestrians was recorded and evaluated.

In addition to the videographic data, four 'roving researchers' or 'spotters' were located on the route, with one notionally designated to each of the four specified crossing zones and nearby, adjacent roads. They invited pedestrians who had encountered the vehicle (e.g. crossed the road in front of it) to complete a survey, which explored their attitudes towards the eHMI design they had seen and the extent to which it affected their crossing experience and behaviour. The survey was hosted on MS Forms and was accessible via a QR code presented to potential respondents at the roadside. Respondents were therefore not required to complete the survey immediately but could return to it later. In total, 64 responses were subsequently received.

Ethics and consent

The study design was approved by the UoN Faculty of Engineering ethics committee. The study employed deception as part of its design. Participants were not made aware that the car had no driver because we wanted to assess their responses to a driverless car, and in particular, the messages displayed on the eHMI. Participants were also not specifically made aware that they were being filmed because the study took place on a publicly accessible area of the University of Nottingham campus. However, the four 'roving researchers' wore high-visibility jackets, and each held a clipboard with details of the survey including a QR code to access it online. The researchers were able to provide broad details about the purpose of the study, if asked, but were told not to reveal any information that may bias the results of the survey, such as if the car was actually driverless. (This question was asked as a validation check in the survey.) Contact details were provided on the survey, and upon request, if anybody had any further questions.

Results: survey

Participants

The majority of the 64 survey respondents were aged 18–24 years (n = 42 or 66%), with the remainder aged 25–34 (9), 35–44(3), 45–54 (4), 55–64(4), 65–74(2), 75+ (0). Most respondents declared 'native familiarity (have lived in UK all/most of their life)' (n = 46) with UK roads as a pedestrian, although there were also respondents who claimed high familiarity (5), medium familiarity (7) and low familiarity (6) with UK roads.

When asked if they believed that the car was driving on its own, over eighty percent (n = 53) of respondents said 'yes' (n = 33) ('There was no driver, just a passenger in the back passenger seat') or 'not sure' (n = 20), with the remainder stating the contrary.

Given the nature of the route taken by the car and each pedestrian's journey, some respondents may have seen one or more of the eHMI designs. Consequently, they were first asked to confirm which of the designs they had seen (or seen most/most recently), with images provided to select from, and tailor their responses to that particular eHMI design. Specific questions relating to respondents' crossing behaviour were also associated with the primary design they encountered, although there were also some questions about their attitudes and opinions more generally.

Clarity, trust and preference

Respondents were asked to describe what information/message they thought the display was trying to convey, how confident they were that this was the intended message, and how much they trusted the message. Respondents could also add written comments to explain their ratings of clarity and trust.

High Anthropomorphism (HA) and Low Anthropomorphism (LA) invited the highest number of positive responses regarding **message clarity** (n = 15/23 and 14/23, for HA and LA, respectively) and **confidence in intended message** (15/23 and 16/23, for HA and LA, respectively) ('I understood that the eyes were looking out for people', 'I quickly became aware that it was helping me to cross', 'It matched observed behaviour of vehicle').

On the other hand, 83.3% (n = 15/18) of respondents stated that Abstract Anthropomorphism (AA) lacked **clarity** (combined ratings of *completely unclear* or *somewhat unclear*), and these respondents generally lacked **confidence** in its intended message ('I wasn't entirely sure what the message was conveying'); only 4/18 stated that they were confident that they had correctly interpreted the information (Figure 4).

A similar pattern emerged regarding **trust**, with most respondents stating that they were either *completely* or *somewhat* trusting of the information for HA (12/23) and LA (n = 16/23), but the converse was true for AA, with only 5/18 indicating that they trusted it ('Would need to encounter it more before I fully trusted it') (Figure 4).

Respondents were subsequently asked to indicate their overall liking of the design they encountered using a 5-point Likert scale, where 1 was labelled 'Don't like at all' and 5 was labelled 'Like it a lot'. Numerical values were also assigned to the remaining scale points and a mean rating calculated. This showed that HA received the highest numerical preference rating (4.1, compared to 3.7 for LA and 3.6 for AA), although mean ratings were not actually statistically different between the three designs (Figure 4).

Crossing behaviour

Respondents who stated that they were waiting to cross the road (n = 43), were asked if they trusted the vehicle to stop. Eighty-six percent (n = 37) selected 'yes', but conversely, 14.0% (n = 6) selected 'no' ('Had seen it…earlier and was curious to see if it would stop or not'). As a consequence (and as one might suspect), 86.0% (n = 37) also stated that they crossed the road in front of the vehicle, whereas 14.0% (n = 6) stated that they either crossed behind the vehicle or took an alternative route/changed their mind. Nevertheless, only 39.5% (n = 17/43) said that they had noticed that that the vehicle was equipped with a display, before making the decision to cross, and only 10 respondents (23.3%) said that it had specifically influenced their decision to cross. In contrast, the majority (n = 25 or 58.1%) stated that they had not realised that that the vehicle was equipped with a display, before crossing (with one person stating that they were unsure), and 55.0% (n = 22) stated that the eHMI had not influenced the decision or that they were not sure if it had (n = 8,

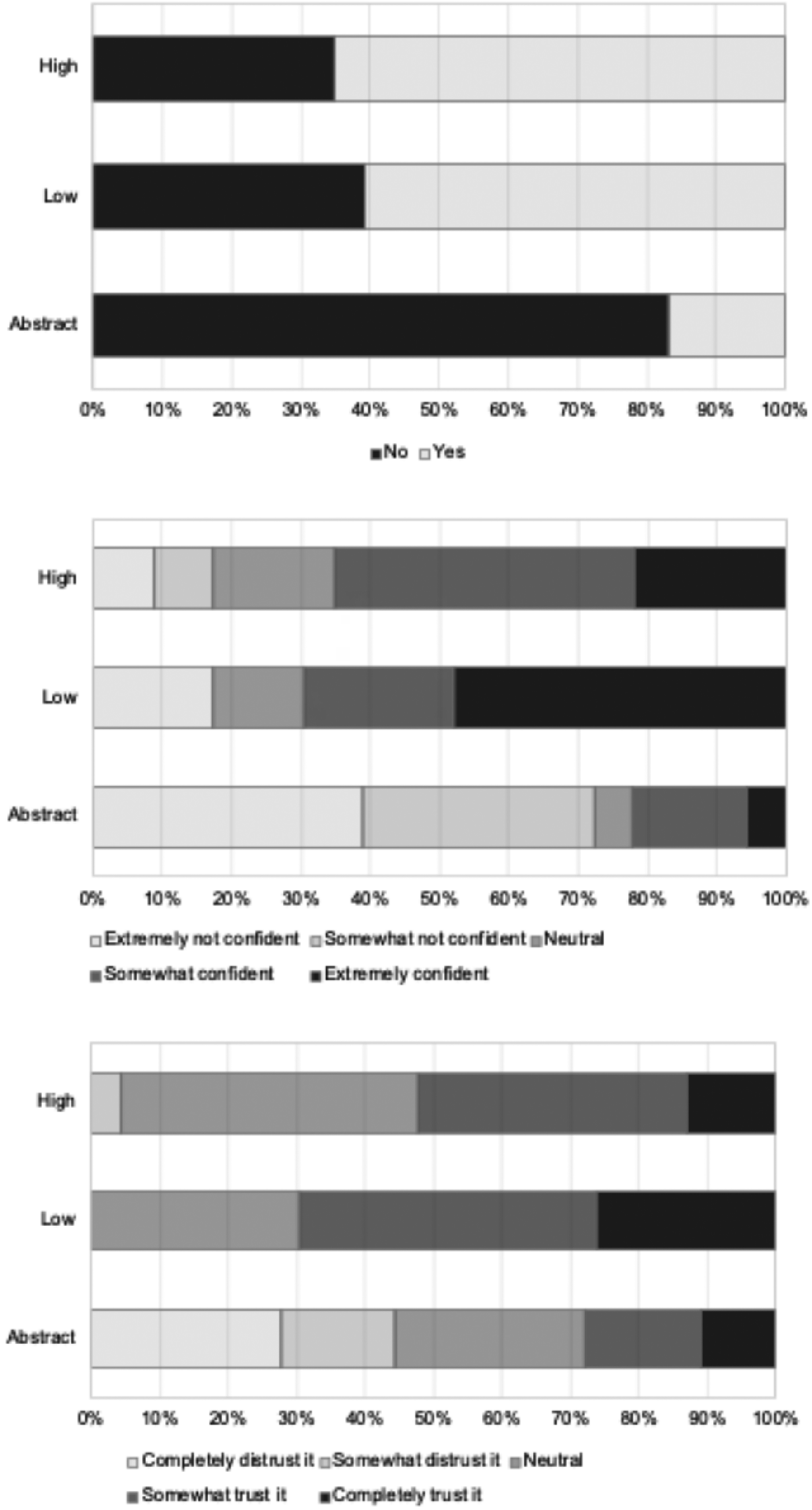

Figure 4.From top: Ratings of clarity (top), confidence, trust and preference ratings (bottom).The figure has 4 graphs comparing results for the 3 eHMI designs. The first 3 are bar charts and show ratings of clarity, confidence and trust as percentages. The bottom is a box plot (or box-and-whisker diagram) and shows a numerical preference for each of the 3 eHMI designs.

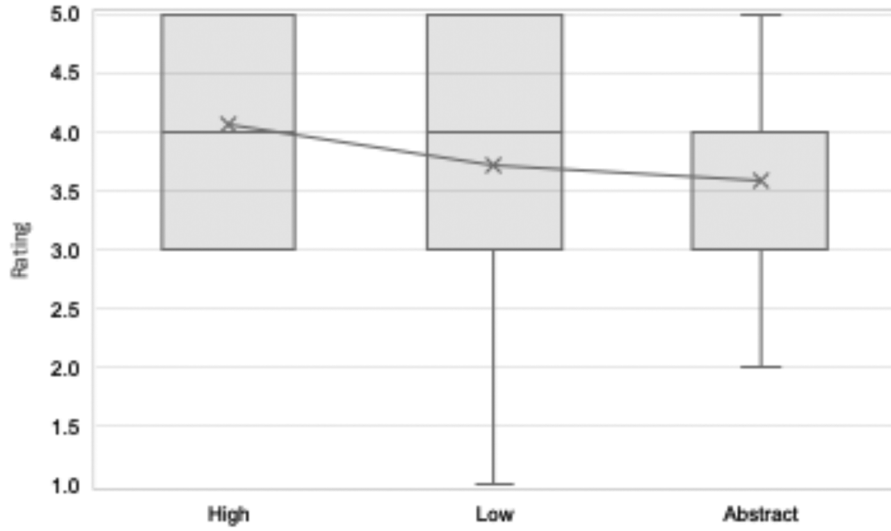

Figure 4. Continued.

Table 2. Information preferences when deciding to cross during the study (left) and expected information in future AV (right).

Item	N (%)	Item	N (%)
Speed of vehicle	25 (40.3%)	Vehicle speed or behaviour	10 (28.6%)
Distance of vehicle from crossing	18 (29.0%)	A gesture or hand signal	9 (25.7%)
Display (eHMI)	10 (16.1%)	Lighting (flashing, signals)	7 (20.0%)
Position of vehicle in road	7 (11.3%)	A sound or audible tone	5 (14.3%)
Behaviour of other people	2 (3.2%)	Eye contact with driver	3 (8.6%)
		Text message	1 (2.9%)

20.0%); responses also indicate that any pedestrians who stated that they were not aware of the eHMI before crossing, subsequently noticed it during their crossing.

Respondents were then asked to indicate what the most important piece of information was when they were deciding whether to cross the road near to the vehicle *on the occasion of the study*. Over 80% of responses (combined) were associated with **implicit cues** relating to vehicle behaviour or road positioning. However, when asked what other information they would expect a vehicle (or its occupants) to communicate to them as a crossing pedestrian *in a future AV*, most responses (combined) were associated with **explicit cues**, such as gestures/hand signals, lights, sounds or text messages, and even eye contact with the 'driver', although it is noted that 'vehicle speed or behaviour' was still the single most-mentioned desirable item. (Both of these questions allowed free-text responses, which have subsequently been coded/grouped, where appropriate, for clarity) (Table 2).

Results: videographic data

Coding scheme

Videographic data were coded using Madigan et al.'s (2019) framework for coding traffic interactions, as applied by (Madigan, Lee, and Merat 2021) . This validated coding scheme was designed to capture the presence, or absence, of particular, observable elements of pedestrian and vehicle behaviour, based on the pedestrian's approach to an intersection (approach phase), their road crossing behaviour (crossing phase) and the behaviour of nearby vehicles (vehicle approach phase and vehicle crossing phase), and was developed with the specific aim of informing AV design.

A notable difference in the current study is that we were only interested in pedestrians' interaction with the study (or ego) vehicle; we therefore did not consider their interactions with, and the behaviour of, other road users. We did, however, code details of the ego-vehicle departing, although this was primarily as a means to record the change of eHMI state, which was synchronised with the behaviour of the vehicle (for example, as the vehicle pulled away, the eHMI was changed from 'giving way' to 'scanning mode'). In addition, where Madigan, Lee, and Merat (2021) coded further characteristics, such as individual/group and potential distractions, as *additional information*, we included these categories within the pedestrian crossing phase, where appropriate (see Table 3 for full coding scheme, or ethogram, applied in the current study). Coding began when a pedestrian of interest was visible at the roadside waiting to cross, or their approach trajectory suggested that they were wishing to cross the road. Coding finished when they had completed

Table 3. Observational data coding scheme (ethogram), based on Madigan et al., (2019) and Madigan, Lee, and Merat (2021).

Action phase	Behavioural category	Descriptors	Notes
Approaching Phase: Pedestrians	Head Movement/Looking at car	Glance (short, less than 1s 'safety check', no obvious fixation), Stare (longer fixation (>1s), 'looking at eHMI')	The pedestrian looks at the car, typically accompanied by head-turning. Defined as a *state* (with start and end times) to enable glance time to be calculated. Could also occur during crossing phase.
	Gesture/Hand Movement	Wave (Intention to cross, Other)	
Approaching Phase: Vehicle	Car approaching crossing		The car is approaching crossing zone
	Car kinematics	Slowing down, Stopped	The car reduces speed on approach to crossing; the car has stopped at crossing allowing pedestrians to cross the road
Crossing phase: Pedestrians	Pedestrian crosses road	Designated Crossing, between crossings (non-designated)	Defined as a *state* (with start and end times) to enable crossing time to be calculated.
	Movements while crossing	Maintained speed (kept pace while crossing), Increased speed, Slowed down gradually, Slowed briefly without stopping, Completely stopped, Crossed behind vehicle/didn't cross	
	Individual/Group	Individual, Group, Coincidence Group	
	Distractions (phone)	Using phone (typing, call, looking/watching content)	The pedestrian has a mobile phone in their hand and is actively engaged in an activity
	Distractions (headphones)	Wearing headphones	The pedestrian is visibly wearing headphones (on, over or in-ear)
	Gesture/Hand Movement	Wave (Thanking driver, Intention to cross, Other)	
Departing Phase: Vehicle	Car begins moving		The car is departing crossing zone

their crossing, noting that they may have crossed in front of or behind the study vehicle.

Interrater reliability

Three experienced researchers coded the videographic data (notionally, coding one day each) using the above framework. One of the four conditions on each day was also coded by a second of the three researchers, resulting in 25% coder redundancy (by duration, i.e. 32.5 mins of the full 130 mins was coded by 2 researchers); this was to establish and ensure interrater reliability. Interrater reliability of the descriptor variables was subsequently calculated using the index of concordance (see Wallace and Ross 2006), which provides a percentage agreement describing the proportion of codes agreed between two individuals as a proportion of all the possible pairs of codes (selected and unselected) i.e. (agreements) ÷ (agreements + disagreements). This method therefore takes into account situations in which coders disagreed, as well as situations where there was a difference in the number of codes assigned between coders. A criterion of 70% agreement between coders was adopted as a reasonable minimum, in accordance with Wallace and Ross (2006) and Olsen and Shorrock (2010), and as applied by Madigan, Lee, and Merat (2021) when deriving and validating their coding scheme taxonomy, upon which ours is based. Results for the current study show that interrater reliability was above the 70% threshold, with 80.3% consensus on day one, 72.2% on day two and 79.2% on day three, giving an overall, mean index of concordance (or interrater reliability) of 77.2%.

Crossing behaviour

Figure 5 shows the number of coded behaviours, expressed per pedestrian. The clustering of behaviours suggests a degree of similarity in pedestrians' crossing behaviour in response to the different eHMIs. Of particular note, is that almost all pedestrians still crossed the road in front of the vehicle, with only 4 recorded instances of people crossing behind it (3 for HA and 1 for NO) (survey data indicated that 6 people had crossed behind the vehicle or changed their mind/didn't cross, suggesting that 2 of these didn't cross and had therefore not been coded in the video data). Moreover, over 80% of pedestrians (in each condition) 'maintained their speed' as they crossed the road, both as individuals or as a group, although there is evidence of some pedestrians stopping or pausing briefly while crossing, often to take a photograph of the vehicle – suggesting that these pedestrians had indeed noticed the vehicle and/or eHMI. The high occurrence of glances made to the vehicle (for all eHMIs) further confirms that the vehicle and/or the eHMI attracted attention. There is also notable evidence of pedestrians subsequently gesturing to the vehicle, with most of these apparently to thank the 'driver' during or after completing their crossing.

In our ethogram, we defined 'pedestrian crosses road' and 'looking at car' as *state* variables, i.e. with a

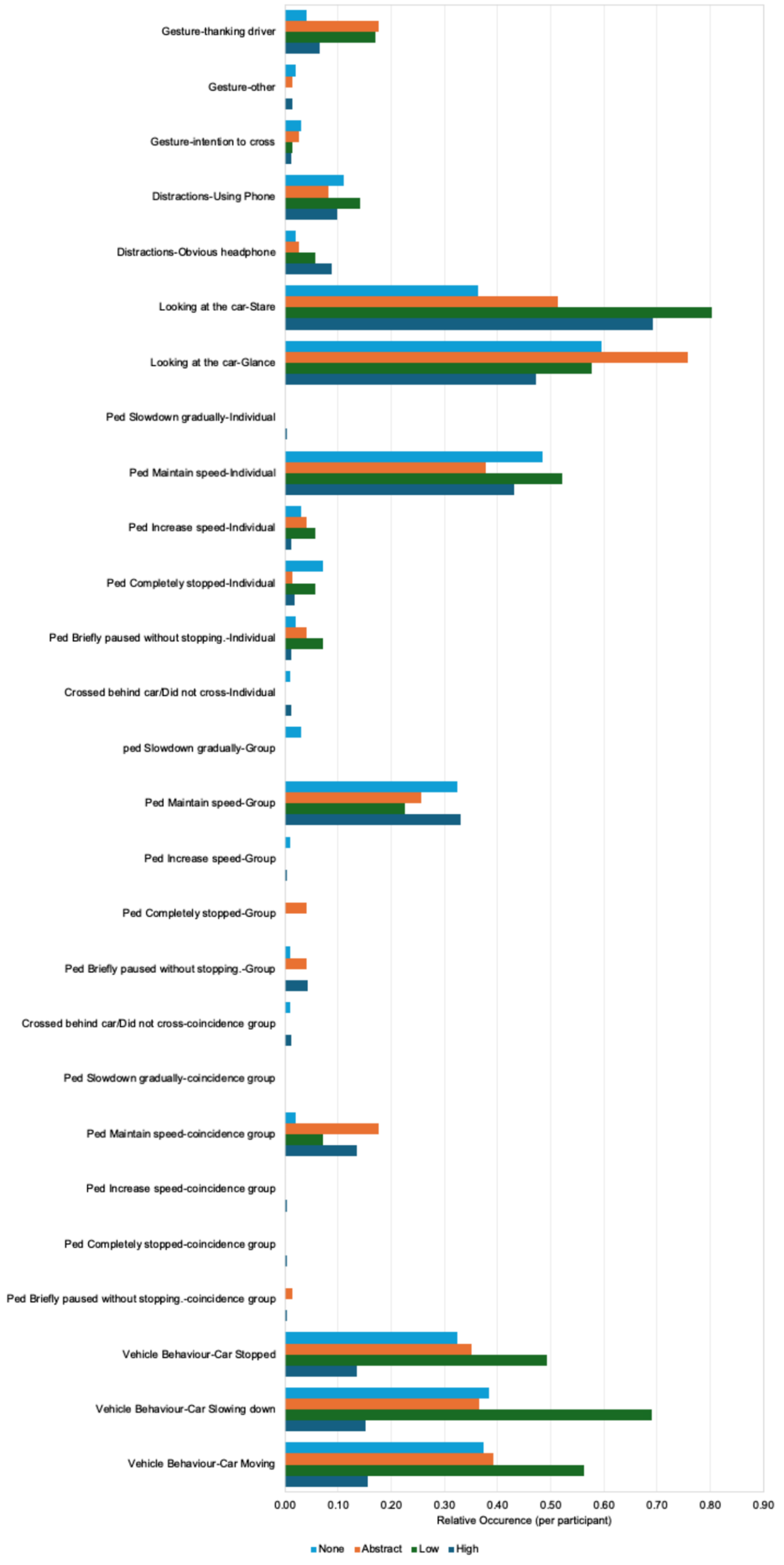

Figure 5. Summary of coded behaviours expressed per pedestrian.

start and end times, thereby enabling durations to be calculated for 'crossing time' and 'glance time' and subsequently compared between the four eHMI conditions. Crossing time and glance time were subsequently calculated for each condition and compared using analyses of variance (ANOVAs). The first ANOVA revealed a significant difference in *crossing time* between eHMIs (F93,210) = 2.8, p = .041), with pairwise comparisons showing that pedestrians took longer to cross the road when presented with HA (M = 8.5s, SD = 2.0s) compared to LA (M = 8.0s, SD = 1.9s) (p = .020) and NO (M = 7.6s, SD = 1.9s) (p = .004).

The second ANOVA revealed a significant difference in *glance time* between the eHMIs ($F(3,279) = 5.7$, $p <$ .001). Pairwise comparisons subsequently showed that the duration of glances to the eHMI/vehicle were longer for HA (M = 2.9s, SD = 2.6s) compared to LA (M = 2.3s, SD = 2.1s) (p = .040), AA (M = 1.9s, SD= 1.6s) (p = .002), and NO (M = 1.9s, SD = 1.7s) (p < .001). Nevertheless, it is also noted that, on average, all pedestrians glanced at the vehicle multiple times during their encounter, with some pedestrians making up to 6 glances, particularly when encountering HA or LA.

Furthermore, as highlighted above, pedestrians continued to use hand gestures to interact with vehicle. This was ostensibly to indicate their intention to cross the road (9 occurrences), or to thank the vehicle or interact directly with the driver (47 and 7 times, respectively), despite the absence of a visible driver. Of note is that, cumulatively, over 12% (n = 63) of crossing pedestrians used a hand gesture. Moreover, there was a higher relative occurrence of gestures, numerically, in response to LA (13/71 or 18.3% of pedestrians) and AA (16/74 or 21.6%), compared to HA (25/276 or 9.1%) and NO (9/99 or 9.1%).

Discussion

Reflections on ghost driver methodology

A fundamental part of the ghost driver methodology (Rothenbücher et al., 2016) is that pedestrians noticed there was no driver in the car and were convinced that the car was driving autonomously. For our study, however, we also required a second person to be present in the vehicle to control the different states of the eHMI, highlight recalcitrant pedestrians to the driver etc. We purposefully did not hide the second researcher in a seat costume, but instead asked them to sit in the back of the car, with the intention that, if they were seen, they would be perceived as a passenger in a robotaxi, and this would in fact reinforce the driverless status of the vehicle. To explore our set-up, we asked open questions about pedestrians' experience, and over eighty percent of respondents indicated that they did not believe that the car was being driven manually ('There was no driver, just a passenger in the back passenger seat'), confirming our ambition. In fact, we believe that those few who were not persuaded of our manipulation primarily comprised one large group of male students, who stepped into the road and approached the side of the vehicle during the first day of the study and subsequently noticed the driver's arms (they were overheard discussing their discovery), and two particularly inquisitive students who followed the car to the waiting area, and may have subsequently observed the driver making adjustments; the seat costume was not designed to withstand such close scrutiny and intended only to convince pedestrians making a cursory glance at the vehicle while crossing or waiting to cross the road. Therefore, from day 2, the roving researchers were also tasked with keeping people away from the car if they became too inquisitive. The video footage also confirms the persuasiveness of our approach, with multiple instances of people who were clearly excited to see the car because they assumed it was self-driving; many of these were subsequently seen taking photos or videos of the car, pointing to it, and discussing it with friends. These observations and the results from the self-report questionnaire showed that the ghost driver approach was successful and allowed us to observe naturalistic behaviour in response to a driverless car with prototypical eHMIs.

Insights on eHMI designs and placement

The eHMIs under evaluation were intended as exemplar designs to showcase different applications of anthropomorphism conceptually and were informed by the literature (e.g. DiSalvo et al. 2002; Ventrella 2011). We notably chose to focus only on visual cues and displayed all messages using the English language. We recognise that this limits the inclusivity and accessibility of our designs, and propose these as important topics for further work. In addition, we aimed to explore different practical implementations and vehicle placements of the eHMIs (see: Dey et al. 2020), notably the use of an LED matrix on the front of the vehicle and an LED strip at the top of the windscreen.

On face value, survey responses suggest that the high anthropomorphism (HA), and low anthropomorphism (LA) designs offered good clarity (HA: 'I understood that the eyes were looking out for people'; LA: 'It was giving way!') and inspired confidence and trust amongst pedestrians. In contrast, the abstract anthropomorphism (AA) was deemed to be least clear ('I wasn't entirely sure what the message was conveying') and had deleterious effects on pedestrians' confidence and trust when they encountered it. Respondents subsequently indicated a slight preference for the HA design, although it is also noted that all designs were generally 'liked'.

In addition, the video footage confirms that pedestrians responded positively to the HA eHMI in particular, for example, by smiling and laughing (based on our observations and field notes during the study, but also corroborated by survey comments – 'A friendly give way!'), suggesting the potential for an eHMI to provide a positive user experience for pedestrians interacting with an AV. Nevertheless, this interest also manifested as longer crossing times and more glances/visual attention directed to the vehicle for the HA design.

It is acknowledged that only a proportion (12%) of pedestrians captured in the video responded to the survey, and it was not possible to associate their responses with a particular behaviour observed in the video. Equally, it is not possible to differentiate a glance specifically made to the eHMI with a glance made to the vehicle, more generally, noting that for many pedestrians it would also probably have been their first encounter with a 'driverless' car. Nevertheless, the more positive responses and additional visual attention appear to correlate with the designs that employed the LED matrix at the front of the vehicle (i.e. HA and LA), whereas eHMIs which only utilised the LED strip (AA) or no eHMI were associated with more negative responses in the survey, fewer glances and more routine crossing behaviour. This suggests that the eHMI did indeed draw pedestrian's attention and suggests potential benefits to using an overt display placed at the front of the car ('very eye-catching; hard to ignore'), compared to a more subtle rendition placed at the top of the windscreen, although further work should consider how to manage the attention it attracts (e.g. precisely what messages should appear, how to encourage pedestrians to return their attention to the road etc.). More generally, results highlight the value of using multiple methods when observing naturalistic behaviour, where attitudes and opinions may only be inferred from video data and further insights may be garnered from a bespoke survey.

Insights on pedestrian road crossing behaviour and expectations

Survey respondents, who were mostly longstanding UK residents, stated that they used implicit cues (vehicle speed, distance from crossing etc.) to make judgements about whether it was safe to cross the road, in keeping with established behaviours and expectations (see: Dey and Terken 2017; Merat et al. 2019). We purposefully drove the vehicle in a defensive manner – aiming to replicate a cautious human driver (see: Hawkins 2018) and to preserve implicit cues, although we recognise that there is ongoing debate regarding whether future, automated vehicle should behave in the same way as current, manually driven cars (especially regarding speed profiles, headway distances etc.), noting that any deviation from established or expected driving norms could potentially impact on implicit cues.

Interestingly, less than half of the survey respondents stated that they had noticed that the vehicle was equipped with a display, before making the decision to cross, and only a small proportion of these specifically stated that the eHMI had influenced their decision to cross. However, all of those who did say that the eHMI had influenced their decision, had been presented with the HA or LA designs, again potentially suggesting the greater conspicuity offered by the LED matrix rather than the LED-strip.

Despite this, there was an expectation from most respondents that a future AV should also provide explicit cues relating to its behaviour, even at designated crossings, with suggested designs including lights and sounds or text messages, and some respondents explicitly stated that they would expect to make 'eye contact' and share 'hand gestures' with an AV – as also highlighted by video footage in which hand gestures were frequently used by crossing pedestrians, who largely believed that the vehicle was driverless. Nevertheless, it is possible that some pedestrians still believed that they were gesturing to a driver. These latter responses and observed behaviours arguably support the use of anthropomorphism in the design of AV-pedestrian interactions and there is also an undeniable logic and perceived legitimacy in using a human-like interface or interaction ostensibly to replace communication that previously took place with a human driver. Nevertheless, there are still significant design challenges to overcome, not only regarding which 'human' design elements to include (and which to omit or replace with other methods of communication), but also to ensure that the exchange of information is accessible and inclusive for all road users.

Analysis of the video data highlighted longer crossing times associated with the HA eHMI, although we would argue that this suggests a greater visual curiosity associated with this design (in addition to the novel experience of interacting with an AV), and its capacity to draw attention, rather than any lack of clarity or indecision associated with the information – a view supported by the survey responses. Indeed, the HA design, specifically, attracted the highest ratings of clarity, confidence and trust. It is also noted that almost all 520 pedestrians still crossed the road in front of the vehicle (in fact, regardless of which eHMI was displayed), although three of the locations we used were designated, marked crossings, and therefore crossing behind the vehicle would have necessitated moving away from the relative safety of a designated crossing.

Limitations and further considerations

The study was conducted on the University of Nottingham campus, and while this is a publicly-accessible space, the population who encountered the vehicle largely comprised younger people (with most declaring their aged between 19 and 24) – a population generally considered to have a greater curiosity and acceptance of new technology. Also, we employed a hybrid study design, in which we wanted to capture naturalistic behaviour, but were also aiming to evaluate three different eHMI designs. It was therefore not possible to balance the numbers of pedestrians exposed to each condition. After considerable discussion on this point, we decided to balance exposure time (approx. 32.5 mins per eHMI) and subsequently coded all the data that was collected, with the aim of preserving all behaviours and attitudes rather than selecting a subgroup of the larger population, in some cases; by expressing results proportionally (e.g. 'per participant') we have attempted to overcome any potential bias towards a specific eHMI design.

We also recognise that, although we have described the vehicle as being driven in a 'cautious' manner and that acceleration and braking were applied 'gently', we are not able to provide specific values for these. Although this may be seen as a limitation (for example, if wanting to replicate our study), our overall aim was to capture naturalistic behaviours in response to different eHMIs. Thus, specific vehicular behaviour may have varied slightly during each approach. For example, the precise onset of braking, and the consequent magnitude of braking force, may have differed if a pedestrian arrived late at the crossing compared to somebody who was already at the roadside. In practice, these were determined by our ambition to always give way to pedestrians. It does also mean that the time available to view the different eHMI states may have differed, but this lack of control is unfortunately a recognised limitation of naturalistic studies.

It is also noted that for the survey, we actively targeted pedestrians who had shown a particularly noticeable interaction with the car, although survey respondents were ultimately self-selecting – there was no obligation to complete the survey, and anybody could scan the QR code. Nevertheless, this may have biased responses to pedestrians who had a particularly positive (or negative) experience with the car, or who had more interest generally in AVs and technology (or indeed, in completing questionnaires). As previously stated, it was also not possible to associate specific survey responses with a specific pedestrian due to both practical and ethical/privacy reasons, although we have attempted to overcome this in our analysis approach. Nevertheless, it is possible that some of the pedestrians who gestured to thank the vehicle, for example, actually believed that there was a driver present whom they were thanking.

Finally, the study presented a novel situation to most people, who may not have encountered a driverless vehicle previously or indeed, seen an eHMI before. Whilst general awareness and acceptance of driverless vehicles may be more common than when the original ghost driver study took place (see: Rothenbücher et al., 2016), there may still have been surprise and/or scepticism associated with the encounter. This may have unnaturally increased the number and/or duration of glances directed to the vehicle during the study (although this would be true for all conditions), but this curiosity would likely reduce over time and repeated exposure. It is also noted that the study, by design, aimed to communicate with crossing pedestrians. Other vulnerable road users, such as cyclists who may approach from the back or side of the vehicle, or indeed, the driver of a manually-driven vehicle behind the AV, who may be unaware of the interactions taking place between the AV and a crossing pedestrian, will require other solutions.

Conclusion

The study applied the ghost driver method to investigate interactions between pedestrians and a driverless car and used anthropomorphism in the design of exemplar eHMIs to provide explicit communications regarding the behaviour, status and intention of the vehicle. Results suggest a desire for, and expectation of explicit communications provided by future AVs. The exemplar eHMIs that were evaluated highlighted the need for clarity and conspicuity to foster appropriate confidence and trust, and to ensure the message is seen and understood. The study suggests that for pedestrians waiting to cross the road, an LED matrix on the front of the bonnet is more visible and can provide more useful information than an LED strip located at the top of the windscreen. In addition, the positive reception to the 'highly anthropomorphic' eHMI design suggests potential benefits of using humanlike interfaces to replace interactions with an absent human driver. However, it is noted that there are many other factors to consider, including the design complexity and information content, that were not controlled as part of this naturalistic study, and further research is needed to validate these findings and indeed, to ensure that any eHMI is accessible and inclusive for all road users.

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