Shape-Changing Interfaces as eHMIs: Exploring the DesignSpace of Zoomorphic Communication between Automated Vehicles and Pedestrians

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Figure 1: We explored the possibility of using shape-changing interfaces for AV-pedestrian communication. We designed eHMI concepts that facilitate biomimicry-inspired communication between AVs and pedestrians, and evaluated them in a focus group.

ABSTRACT

External human-machine interfaces (eHMIs) are shown to support Automated Vehicles (AVs) in interacting with vulnerable road users such as pedestrians. Typically, eHMI concepts are light- or sound-based designs that communicate the AV’s intention with abstract visualizations, which are unfamiliar, not fully intuitive, and require learning. In the natural world, animals are shown to communicate their intention or disposition with a variety of visible reactions, using posture, gesture, or other means, which have implicit meaning by association with centuries of evolution. We explore the design space of biomimicry-inspired communication between AVs and pedestrians using external Shape-Changing (eSC) interfaces. We created six distinct concepts of eHMIs that employ external shape change and evaluated them in a focus group. Results show that zoomorphic, shape-changing-based eHMI concepts are promising in achieving intuitive communication about an AV’s intention in traffic. This may help in reducing the learning effort associated with abstract eHMIs, and ease the integration of AVs.

CCS CONCEPTS

• Human-centered computing → Interaction design; Interaction techniques.

KEYWORDS

Automated vehicles, External Human-Machine Interfaces, eHMI, Shape-changing interfaces, Biomimicry, Vulnerable Road Users, VRU, Pedestrians, Vehicle-pedestrian interaction

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1 INTRODUCTION

In the absence of human-centric cues such as eye contact or gestures, external Human-Machine Interfaces (eHMIs) have been proposed to facilitate AV-pedestrian interaction [15]. Although research in eHMIs has shown promise in mitigating ambiguity and streamlining interactions, there is no consensus on the ideal form of an eHMI, as evidenced by the 70+ eHMI concepts identified and categorized in recent work [4]. Current designs of eHMIs heavily use light-based
Figure 2: Examples of external Shape Change currently demonstrated in vehicle concepts. Clockwise from top left: Mercedes-Benz AVTR concept, BMW Vision 100 concept, BMW Lovos concept, and BMW Gina concept.

designs that communicate the intent of an AV through abstract visualizations [4]. There is a literature-backed argument why other forms of non-abstract visualizations are ill-suited for eHMIs, and the abstract design is a choice made out of necessity [12, 21]. However, the biggest disadvantage of abstract visualizations lies in its inherent ambiguity by virtue of the design being abstract. Such eHMIs need to be learned, and are often not intuitive – leading to hesitation and confusion, as evidenced by several studies on eHMIs [16, 17]. Thus, it is an open question how to design intuitive eHMIs that communicate the intention of AVs to pedestrians.

In this paper, we set out to explore the role of biomimicry in designing eHMIs for AV-pedestrian interaction as one approach towards more intuitive interfaces. Communication of intent through gestures and movement is common in the natural world [2, 13, 22], and lends itself to a high degree of intuitive understanding of the mood and disposition of an autonomous agent. We expect this effect to extend to the context of automated vehicles' intent and driving behaviors. Previous research has shown that a vehicle's kinematics and movement patterns play a significant role in communicating its intent [3, 8, 18]. Vehicle kinematics can also be thought of as the “body language” of the vehicle, and this further supports the notion that movement- and gesture-based communication can be more intuitive forms of communication than abstract visualizations. To this end, we investigated the potential of biomimicry-based zoomorphic eHMIs through external shape-changing (eSC) interfaces.

The use of external shape-change (eSC) as a concept is not new in the automobile industry. Various forms of shape change such as deployment of spoilers, pop-up headlamps, folding mirrors are common in cars. Recent concepts, however, have extended these common applications of shape change to improve aerodynamics, impart a sense of personality to cars, or even evoke emotions in people, as evidenced by the examples in Figure 2. However, using biomimicry-based shape-changing interfaces as a means of communication is a new and under-explored topic. The Mercedes-Benz AVTR concept uses zoomorphic shape-changing “feathers” on the back of the car to impart a sense of sentience and personality to the car. One of the eHMI concepts by Dey et al. [6] named the “Hedgehog” proposes similar “feathers” on the hood of the car that deploys according to the driving or yielding intention of the car. This was done with inspiration from deimatic behavior as observed in the natural world – where animals can show pacificistic or agonistic disposition (friendly or threatening attitude) by changing the shape of their body, fur, spines, or feathers in accordance with aggressive or submissive attitudes. Another concept by Eguchi et al. [10] uses inflation and deflation to indicate one of three modes: manual driving, automated driving/platooning, and yielding to a pedestrian.

2 SHAPE-CHANGING INTERFACES AS eHMI

Past research has shown that movement and unexpected changes in direction of motion can attract attention [1]. This insight, along with knowledge on how behavior and disposition is communicated in nature through movement [20] allow us to explore zoomorphism in eSC and evaluate its viability as eHMI. We created six eHMI concepts (choosing the bumper/hood of the car as the placement

Figure 3: The shape-change based eHMI concepts evaluated in the focus group. For each eHMI concept A through F, the beginning and the end of the transformation are shown next to each other.

location, as this has been shown in the past to be a suitable location for eHMIs [9, 11]. To test if the concepts show any promise, we conducted a preliminary qualitative evaluation of the concepts through a focus group. We chose the scenario where an AV approaches a pedestrian who is waiting to cross a road, and therefore visualized the eSC-based eHMI concepts from the point of view of a pedestrian. The vehicle on which we modeled the different eSC-based eHMI concepts was a Tesla Model S. A 3D model of the vehicle was used as the basis to implement the different eSC-based eHMIs using SolidWorks. We rendered the videos in Keyshot, as shown in Figure 1. The videos showed a gentle yielding behavior of the AV as proposed by Dey et al. [7]: The vehicle slowed down to a complete stop in front of the pedestrian, while visualizing the different eSC behaviors in separate videos. We conducted the focus group with $N = 6$ participants (age range 19 – 65 years), with diverse backgrounds. The designs (A – F) are shown in Figure 3, and the concepts along with the feedback we received are described below.

**Design A – “Wings”**
This design incorporates two 'plates' on the hood of the car that deploy sideways. The biomimicry metaphor used in this concept is that of wings, to reflect how a bird streamlines its wings in cruise flight, and deploys its wings to induce aerodynamic drag to slow down and land. In general, the unfolding or deploying of the wings were perceived as an indication of slowing down, and people associated a folded wing with acceleration. The metaphor of increased aerodynamic drag was perceived by 5 (out of 6) participants, and some spontaneously mentioned an association with a bird’s wing (P4, P6), which was our design vision. This concept was regarded as “pleasant” by three participants (P1, P5, P6).

**Design B – “Balloon”**
This design uses a malleable surface on the hood which communicates via inflating or deflating, using the biomimicry metaphor of a display of submissive disposition. The inflated skin can make the car look friendly and approachable, and may be likened to a balloon or a soft padding. Opinions regarding this concept were highly split. The inflation of the stretchable skin on the hood was associated by two participants with braking (P4, P5), and was likened to a deploying airbag by two others (P1, P3). Participants also associated this transformation with the metaphor of a rhinoceros’s horn (P3), or an animal arching its back and raising its hair (P5). This concept evoked the sense of being “unpleasant” (P1, P5) and “threatening” (P3, P5), and did not turn out to be an acceptable design.

**Design C – “Bowing down”**
This design uses transformation of the suspension and chassis of the car to make the front of the car tip downwards, alluding to the metaphor of a bow as a submissive gesture. When yielding, the car can bow to communicate its intention to pedestrians. This is also in line with the natural behavior of a car when slowing down - due to the physics of vehicle kinematics, braking causes the front of the car to pitch forward slightly. This concept thus also exaggerates the external attribute of a stopping behavior. Participants generally associated this movement with braking (P3, P4, P5). One participant (P5) also interpreted this behavior as a bow, as if the car wanted to communicate, “After you” – which was the intended metaphor of this design. However, some participants also noted that the exaggerated movement lent itself to a belief that the car was braking hard, which extended to an unsafe feeling (P2, P4).
Design D – “Airbrakes”
This design uses small panels on the hood of the car (scales) that deploy by rising up in a rotational motion. This concept is an adaptation of the “hedgehog” concept proposed earlier by Dey et al. [6]. The metaphor is again one of increased aerodynamic drag induced by the deploying feathers or scales when the car is yielding or slowing. This was another well-liked concept where the deployment of the rotating scales on the hood of the car in this concept was generally associated with braking (P3, P4, P5) due to an association with increased aerodynamic drag, which was the intended metaphor behind this design. One participant (P3) likened it to a spoiler or speed brakes on the wings of an airplane. Others associated this deployment with the tail feathers of a bird coming to land (P1), or an animal raising its hair (P5).

Design E – “Bowing forward”
This design transforms a part of the vehicle body – the front of the hood – by extending and retracting it along the length of the car’s profile. The metaphor is again one of extending a bow as a signal of yielding or submissive behavior, but instead of tipping the front of the car downwards, this design extends the front of the car forwards. While the vision behind this concept was a different execution of the bow as in Concept C, the extension of the front part of the vehicle along the length of the vehicle meant that from the point of view of a pedestrian waiting to cross the road in front of the vehicle, the transformation was not noticeable. As a result, this concept was not successful in practice.

Design F – “Anglerfish”
This design uses modular sub-vehicles that transform the car’s shape by adding to or subtracting from the main body of the car. The metaphor in this concept is one of the anglerfish, which uses an “angler” to draw attention and act as a bait. Although the purpose of the modular sub-vehicle is not to act as a bait in our case, we conjectured that an eHMI that detaches and independently but cohesively moves with the car, can catch attention, and opens a wide range of new design possibilities. The modular sub-vehicle, in this case, is a drone that travels along with the car at an elevated level while cruising, and returns to the hood of the car when it is yielding or stopping, he integration of the sub-unit of the vehicle with the hood was unanimously seen by all participants as a metaphor for braking. Some participants (P2, P3) associated the subtraction of the sub-vehicle from the hood (the drone moving out of the hood of the car) with acceleration because of the metaphor of an arrow leaving from a bow. Most people except one (P5) found the concept pleasant.

3 DISCUSSION
In creating these concepts, we recognized that some of the zoomorphic metaphors in the eHMIs were tenuous. Others showed some potential weaknesses when visualized, and some can lead to contradictory perception based on the perspective and interpretation. This is why evaluation of such concepts at an early design phase is critical. The thematic analysis of our focus group revealed interesting associations between some transformations in exterior shape change and intuitive perceptions regarding their meaning. There were specific associations with expressions of braking behavior, and other associations that arose from a likeness with “gestures”. The association of aerodynamic drag was prevalent with eSC that incorporated transformations involving an increase in size or volume. Surfaces that changed shape by getting bigger were associated with greater induced aerodynamic drag, and in extension, braking. Furthermore, the association with vertical motion of a vehicular sub-unit as shown in Concept F with the speed, distance, or time-to-stop of the vehicle was unanimously recognized. This is similar to the various distance-dependent anticipatory eHMIs proposed in literature [5], and should be explored further. Additionally, movement of the vehicle’s body that are in line with the pitching movement as a result of vehicular kinematics was well-received and easily understood as deceleration. Furthermore, the tendency to associate gestures with intention communication is strong. For instance, the movement of the body panels in Concept A (“Wings”) was indeed associated with wings spontaneously, and in extension, also associated with a sweeping gesture.

Research shows that representational characteristics in icon design play a role in recognition and compliance [14]. Our focus group feedback on the proposed zoomorphic eHMIs show that there is a potential of meaningful association of metaphor with such kinds of eHMIs. Prior work on bio-inspired eHMIs were not promising in favor of shape-changing designs [19]. However, we note that the concepts tested in the study were not validated for viability. Our own results show that not all eSC-based eHMIs are equally favorable, and some can be ineffective, or even counter-effective based on interpretation or perception. Nevertheless, it was clear that certain shape-changing interfaces evoked intuitive responses about the meanings of a transformation, potentially because they offer communication thorough movement in three dimensions in space rather than two-dimensional abstract, light-based designs. Thus, even if eSC-based eHMIs are not infallible in their intuitiveness, they have the potential to add a layer of clarity by their representational design of familiar metaphors and icons compared to light-based abstract designs. This can improve the learnability and aid the acceptance of AVs. However, at this stage, these insights should be considered as inputs for hypothesis generation rather than treated as confirmatory results.

Future Work
Given the potential of eSC in eHMI applications, and armed with the knowledge that not all eSC-based eHMIs are equally effective, the next step is to explore the design space of exterior shape change in greater detail in the creation of novel eHMI concepts. We are in the process of conducting thorough empirical tests to compare their effectiveness with other forms of eHMI, and in different situations varying in complexity.

4 CONCLUSION
This paper explored the design space of zoomorphic exterior Shape Change (eSC) in the context of eHMIs for AV-pedestrian communication. We designed and evaluated six eSC-based eHMI designs in a focus group, and found that while not all eSC-based eHMIs are equal, they have the potential to invoke meaningful associations in communication. Our initial results highlight that their inherent
representation association with natural metaphors can lead to an intuitive communication of intent. We conclude that the design space of eSC holds promise as potential eHMI solution in facilitating effective communication between AVs and other road users, and should be explored further in the future. This can potentially reduce the learning effort associated with abstract eHMIs and improves the integration and acceptance of AVs.

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