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Driving in Roundabouts: Why a Different Theory of Expert Cognition in Social Driving Is Needed for Self-driving Cars

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Abstract

This paper considers the study of driving skill and performance of human drivers as a key domain to improve the design and the "expertise" of self-driving cars. Concerted driving with others in roundabouts is a special kind of social expertise —understood as competence in ordinary, mundane activities— deployed by members of society. We illustrate our theoretical arguments about how human cognition works in driving contexts with the analysis of three paradigmatic examples through the lenses of the ecological framework. Based on these analyses, we discuss the need for a more robust and realist theory for developing self-driving cars as potential complications arising from interactions between human drivers and self-driving cars cannot be solved with current socio-cognitive models for decision-making and social coordination. The ecological framework considers that drivers' exploratory activities rely on the utilization of affordances, rather than on the internal processing of information, which is currently the default assumption guiding self-driving car design. The ecological approach assumes that drivers are embedded agents that act within increasingly complex technological envelopes. Such a framework could be used to investigate how digital driving landscapes may be closely tailored to the drivers' activities. Finally, future research on driving design should investigate how affordances can be matched with emerging digital technologies for reducing accidents and improving traffic flow.

Keywords

Self-driving cars, affordances, membership, ecological psychology, roundabouts, self-organization

Introduction

It has been eight years since the first self-driving car officially drove in the streets of a few states in the U.S.A. The self-driving vehicle originally developed by Google operates with a navigation system and promises to open new horizons in the transportation field.[1] Car companies such as BMW, General Motors, Honda, Mercedes, Nissan, or Tesla are all developing their own prototypes, competing to win the automated cars race. "Digital giants" such as Apple or Baidu are also on the run and have invested in their own automation programs. The potential industry of automated cars is considered an extremely promising business by private promoters but is also regarded with interest by the government. Indeed, on January 14, 2016, former U.S. Transportation Secretary Anthony Foxx announced several initiatives of the department to promote innovations in vehicle safety including a $4 billion ten-year program for automated vehicles implemented by President Obama (DOT, 2016).

To date, only a few traffic incidents involving self-driving cars have been reported.[2] In 2016, Google took the blame for an incident involving its self-driving car for the first time (Sleek et al., 2016). In this incident, the self-driving car was driving in the left lane when it encountered a sandbag on the road. The car decided to merge into the middle lane, assuming that an incoming bus would yield. However, the bus driver also assumed that the self- driving car would wait for the passing bus before changing lanes. As a result, the bus ran into the car.

The self-driving car followed the traffic rules strictly and could not adjust to the possible interaction with other vehicles. This specific incident is very telling about the differences between driving performance by humans and self-driving cars. Moreover, it also reveals the sort of problems that may arise when human drivers and self-driving cars meet in the streets, a likely occurrence in the future.

The assumption of Google's self-driving car developers is that traffic problems (e.g., accidents, jams) are a result of people misbehaving and not following traffic rules, which implies that transportation would occur without any problem if every car always followed those rules. Thus, although this driving heaven is impracticable in a dynamic world with human drivers, self-driving cars could turn it into a reality.

In this study, we suggest that driving incidents are not simply a matter of people not following traffic rules. We argue that traffic rules act as boundaries or constraints to the drivers' activity. These constraints are useful for coordinating the drivers' actions toward one another; i.e., traffic rules are constraints that channel the interactions between drivers, although without determining the driving activity per se. Traffic rules do not prescribe successful driving activity, neither alone nor in conjunction with other rules. Thus, in large part the driving activity is not—and cannot be—determined by driving laws.

The main challenge is to eradicate or attenuate the mismatch between the detached rationality of the programmers, who code the self-driving cars' software, and the embodied, ecological cognition of human drivers. As Gibson admonished long time ago, driving theories "…should adopt the driver's point of view rather than the safety engineer's, should start from normal rather than abnormal driving, and should emphasize what the driver ought to do rather than what he ought not to do." (Gibson & Crooks, 1938, p.471).

To improve the design of self-driving cars, we aimed to construct a theoretical framework incorporating the driving activity of human drivers by studying how people drive in roundabouts, which is a specific setting with dense human interaction. The purpose of this opinion piece is to explain human collective interaction through the ecological framework—and to propose new aspects for developing models of self-driving cars and improve their function in human settings. Based on the assumption that self-driving cars strive to interact with humans, we see roundabouts as a significant potential problem for traffic when these two types of drivers come together. And, because roundabouts are widespread in Europe and Australia and more recently in the U.S.A., consideration of this problematic is valuable worldwide.

The structure of the paper is as follows:

- The first section presents an initial analysis of a case study in which we describe what it is like to drive with others at a roundabout following *more* than plain traffic rules.
- The next section uses the analogy of driving with others as a team sport to discuss two contrasting models (social-cognitive and ecological) that have been used in the analysis of interpersonal coordination and decision-making in sports.
- Building upon the previous discussion, the third section opens the possibility of the consideration of driving with others from an ecological perspective. It analyses two case studies in which the use of shared

affordances is key for driving with others at a roundabout.

- The last section discusses the implications of introducing the ecological model in the design of self-driving cars and questions the assumption of replacing human drivers for automated cars altogether as the best option. It also proposes future lines of enquiry that will contribute to the commensurability of human and non-human drivers.

Membership as Expertise in Driving Within Roundabouts

Roundabouts are circular intersections where cars flow in one direction around a central island. They can be considered as a valuable solution for making traffic safer and more fluid when compared to other types of intersections. Roundabouts have specific traffic regulations (i.e., how to enter, circulate inside, and exit), but we believe that these rules work only in ideal, textbook-type situations. For instance, the Spanish General Traffic Direction (DGT) guide gives the following general principles for driving in roundabouts:

> Give way to those inside the roundabout and choose the most convenient lane for the desired exit; once inside the roundabout the circulating car has preference over the accessing one; to exit the roundabout cars must get into the most external lane; and if not possible, they must do another turn to have enough time to get into the right position (…). Take into account that there are no predetermined lanes for specific exits: The roundabout is a one-way route, generally with some lanes, with exits located on the right side. (Rodríguez, 2014, p.28, our translation)

Even in this ideal situation, the general rules say little about the local decisions made by drivers and their capacity of inter-personal coordination. Concerted driving in situations of heavy interaction such as roundabouts demands a different kind of expertise when compared, for instance, to car motor racing, which is predicated on the drivers' ability to master coordination patterns for acceleration, braking, and steering at very high speeds (see Rosalie & Malone, 2019 for a study of expertise in formula car racing).

Concerted driving in roundabouts is less demanding on such coordination patterns but radically more social in essence. The kind of social expertise needed for concerted driving with others is related to what Garfinkel (1967) considered members' competence.[3] In the specific case of driving with others, members are experts of the ordinary, mundane activities of society. Thus, membership demands only a special kind of expertise: You do not need to be Lewis Hamilton in order to drive with others to solve a myriad of ordinary situations in the roundabouts. Even so, the picture can become complex in situations of heavy traffic when people self-organize to go through the roundabout while maintaining traffic fluidity. It is likely that in these situations there occurs a "…spontaneous emergence of interpersonal mode of actions when the situational constraints demand them" (Marsh, et al., 2009, p.327).

We suggest that maintenance of traffic fluidity on roundabouts, as well as the positive tradeoff between fluidity and accidents, would be impossible if every car followed the rules on every occasion. A study conducted in Spain about driving in roundabouts (AXA, 2016) showed that even though almost half of the drivers did not know the traffic rules correctly, only 5% of the total sum of traffic accidents occurred in roundabouts.

Thus, drivers must acquire driving methods that go beyond those specified by the traffic rules. Those practical methods qualify them as competent members of the driving community (competent drivers). In fact, driving in roundabouts is in itself a case of embodied, ecological cognition, which implies more active and pro-active behaviors than simply executing the behaviors established by the driving rules.

For people driving together, those behaviors imply a local orderliness. Local refers to the following: (1) a specific country where different driving norms apply (compare driving in a roundabout in the UK [going clockwise] and in continental Europe [going counterclockwise]);

(2) the specific setting of each roundabout, where some idiosyncratic methods for driving have been concerted and iteratively honed by those who have been driving there since that setting existed; (3) different conditions of traffic density (compare driving in a roundabout during off-peak or peak hours); and (4) the fact that the search for a solution to the problems of driving with others in a roundabout is a moment-to-moment deployment of concerted actions through practical methods of driving. These different but related issues suggest that there is no need for a general theory of traffic flow to be applied to particular places and times, nor for a complete knowledge of the specific situation of each car in the roundabout. In fact, such theory may be misleading to explain driving behavior.

Each roundabout embodies a context comprising what Rietveld and Kiverstein (2014) consider a "rich landscape of affordances." As these authors remark, the use and engagement of—and with—affordances (possibilities for action; see below) always involves utilizing an aptitude within a specific context (2014, p.326). Thus, we cannot establish or define general affordances for driving in roundabouts; instead, affordances should be established or defined in respect to the specific context of each roundabout. As an example, we analyze the specific case of the Boadilla del Monte roundabout.

Boadilla del Monte (Madrid, Spain) Roundabout

In this roundabout (Figure 1), we can observe the dynamic production of a local orderliness of "driving in a roundabout" by the coordination of the drivers. One of the authors has been driving through this roundabout daily during the past seven years. The time is 2:30 p.m., and the rush hour is unfolding as the footage was recorded (Figures 2-5).

The first irregularity that caught our attention was that two cars on the right-hand side of the image (red and black) are sharing the external lane (Figure 2a-c) even though this is not permitted by traffic rules.

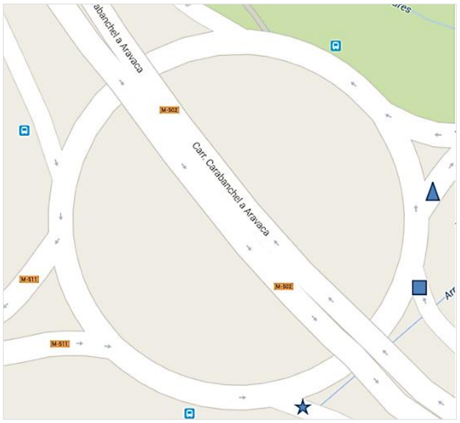

Figure 1. Roundabout in the road to Boadilla del Monte, close to the city of Madrid, Spain. The star marks the next exit in the footage; the square marks the entrance of cars; and the triangle marks the after-next exit in our analysis. Adapted from Google Maps, https://www.google.es/maps/@40.3999233,-3.7795822,18.01z

Figure 2a (0.19 s) **Figure 2b (0.27 s)** **Figure 2c (0.29 s)**

Figure 2a, 2b, 2c. Red and black car sharing the external lane for two different exits.

These cars are using the external lane for different purposes. Whereas the black car is trying to reach the coming exit (the star in Figure 1), the red car needs the external lane to be in a good position for the after-next exit (triangle in Figure 1), which will be shared with cars incoming from the central lane (white car, for instance).

The second irregularity to notice in Figure 3 is that two cars in the external (red car) and central lanes (white car) that are both heading to the after-next exit (triangle in Figure 1) stop at specific times to allow other cars entering the roundabout (square in Figure 1). They stop precisely when the flow of cars in the after-next exit is stopped (see Figure 3a, b, c); as there is no gain in proceeding to the exit, these cars give way to the incoming cars on the roundabout.

Figure 3a (0.50vs) **Figure 3b** (0.55 s) **Figure 3c** (0.57 s)

Figure 3a, 3b, 3c. White and red cars stopping and giving way to the black car entering the roundabout.

Again, the action indicated in Figure 3 clearly contravenes traffic rules, which specifies that cars driving in the roundabout have priority over those entering the roundabout. If every driver followed this rule strictly, the cars coming from the entrance road would never be able to enter the roundabout until the rush hour was finished, and this would have consequences in the traffic of other roads connecting to the roundabout. Moreover, to advance, the black car entering the roundabout broke the driving code by crossing two lanes to reach the inner lane (Figure 4c, trajectory marked with a red dotted line), as the cars waiting at the after-next exit were blocking both central and external lanes. When traffic flow resumed, the cars that were giving way started advancing again (after 23 seconds, 0.50s-1.13s on the clip), thereby blocking the entrance to the roundabout (Figure 4).

Figure 4. (1.13s) Cars in the central and external lane resume driving as cars in the after-next exit have started to advance again.

Then, cars in both the central and external lanes proceeded to share the after-next exit (see Figure 5a, b, c). Traffic rules mandate that only cars in the external lane are allowed to exit a roundabout; cars in central lanes should position themselves with enough time and space in the external lane before taking the exit. However, this is virtually impossible in a rush hour situation. In this example, there were so many cars arriving at the same time at the roundabout and aiming for the after-next exit that drivers in both central and external lanes had to coordinate a loose “zipping” strategy (one car from each lane taking turns) for exiting the roundabout.

5a (1.16 s) **5b** (1.18 s) **5c** (1.21 s)

Figure 5a, 5b, 5c. White and red cars sharing the after-next exit, using a "zipping" strategy.

The different driving actions portrayed in this example show how drivers self-organize (i.e., they organize among themselves without any one person controlling the other) to drive through the roundabout taking into account much more than what is prescribed by traffic rules. This example shows at least three driving actions that blatantly contravened traffic rules but were reasonable (and necessary) for maintaining a fluid traffic flow.

Driving with Others as a "Team Sport"

When one understands driving as a teammate-adversary game where the players' roles are constantly changing, the activity of driving in roundabouts can be comparable to collective behavior in sports.

Cooperation and opposition between players shift, yet the overall effect is that drivers coordinate their actions to achieve their personal goals (to exit at a specific space) while maintaining the collective goal of ensuring traffic flow (and consequently avoiding accidents). Moreover, although some drivers are more selfish than others, this does not interfere with the tight bond between personal and collective goals. Indeed, every driver needs to coordinate with the others to avoid a traffic jam, which would delay their journey for an indefinite amount of time.

This is not to say that such coordination is an easy task. As Levy et al. (2016, p.1) state, the drivers' understanding of traffic is limited, as they are "…constrained to a local view of traffic, spanning a few cars in each direction, depending on the terrain, and lack a global view of streaming or jamming traffic with incoming and merging lanes." These authors also remark that drivers are not aware of the emergent collective patterns arising from the complex traffic system. For instance, the common behavior of constantly changing lanes while in a traffic jam does not benefit the flow of traffic for anyone (not even for the driver performing these actions). Counterintuitively, in these situations "slow is fast," therefore "by avoiding such sources of turbulence in the system the collective cars' average speed raises, possibly reaching a coordinated phase of traffic (dense and fast), the sweet spot for driving in congestion" (Levy et al. 2016, p.1).

While such analysis from complex dynamic systems is paramount to understand the flow of traffic, we still need to understand how and when drivers make decisions that allow them to coordinate with others for achieving personal and collective goals.

To understand the type of decision-making and interpersonal coordination in goal-directed driver activity in roundabouts, we discuss these topics in the context of sports research by contrasting the social-cognitive and ecological approaches. We believe that it is vital to make clear the differences between these approaches because problems underlying the interaction of self-driving cars and human drivers do not necessary result from the typical human behavior of not complying with traffic rules. Instead, we believe these problems are more deeply rooted. Specifically, they are a consequence of the self-driving car design, which is predicated on a social-cognitive model at odds with human cognition (as argued by the ecological framework). Self-driving cars and human drivers do not "talk the same language"; the former are "blind" to emerging opportunities for human interaction when driving.

Interpersonal Coordination and Decision-making in Sports

Team and interpersonal coordination in sports has been studied with different paradigms (see Araújo & Bourbousson, 2016 for a review). We propose that driving in general but driving in roundabouts, in particular, could benefit from the large body of knowledge amounted in those sports studies.

But driving is not a sport. In contrast to the sports context, the intention to trick or fool others is highly reduced, if not absent, in the driving activity, because one's own safety is at risk. Safety is also the reason why drivers aim to make their behavior conspicuously clear when coordinating with others. Nonetheless, not every driver displays signals properly every time (e.g., using indicator lights). In fact, drivers are often careless with other cars, possibly because they believe that their actions display enough information for others to regulate their own driving behavior accordingly.

The social-cognitive approach assumes that coordination in a group of players depends on their shared knowledge: the greater the degree of sharedness, the better the coordination. Thus, team members must share a similar understanding of the game to form clear expectations about each other's actions; such shared knowledge explains the coordination between players to achieve performance goals.

The concept underlying this assumption is a common information-processing postulation: Performance is determined by a representation or schema in the player's mind; hence the players must share beforehand some abstract information (e.g., schema, representation) about their objectives (i.e., task and teamwork) in order to work efficiently together (Cannon-Bowers et al., 1993).

In this information-processing paradigm, cognition can be defined as a computation of symbolic representations, with the brain working as a computer to perform that processing. Cognitive processing occurs not only in the decision-making phase, but it also heavily influences the perception and action phases, as sensory inputs from the environment are cognitively transformed (due to memory) to (1) attribute meaning to those inputs; (2) convey information on what type of responses to take and (3) implement appropriate motor responses (via a motor program). Indeed, there is an attentional system responsible for selecting and distributing cognitive demands during these different phases and a memory system (short term or working memory and long-term memory) that stores information to be retrieved for comparing with previous situations. The role of explicit memorized knowledge, encoded and retrieved by each player, is paramount for successful team coordination (Eccles & Tenenbaum, 2004).

As a game implies a dynamic set of interactions, a constant renewal of shared knowledge between the players is necessary for them to adapt to different game situations. This intrinsic dynamic of the game implies that each player continuously updates his/her representations, and this must be coordinated with the teammates.

The current default self-driving car design adopts the social-cognitivist assumption to explain navigation and coordination with other drivers: Shared *a priori* representations of each situation are needed for decision-making and coordination between human drivers and self-driving cars. The car is equipped with a very advanced set of sensors: on top of the car there is a 360^0 high-resolution camera that can scan sixty meters in any direction; there are also three front radars and one rear radar to detect near objects. The car's software recognizes what kind of objects the sensors are detecting (people, cars, road signs) and is also responsible for the car's compliance to traffic rules. Such detection system of sensors/software combined with GPS localization on a digital map allows the car to have a clear representation of the driving situation and therefore to make rational decisions while driving. Based on these representations stored in its computational memory, the car is expecting the same navigation style from other cars, i.e., some type of shared knowledge with the other drivers/cars about the situation, the specific goals of each driver and the traffic rules to be followed by everyone taking part in the "game."

Traditionally in psychology, human decision-making has been considered a rational process (Shafir & LeBoeuf, 2002). Rationality works in closed systems whereby specific conclusions can always be derived if a rational reasoning process is followed and there is sufficient information and preconceived assumptions about the problem (Hammond, 2007). The rational model rests on the assumption that drivers can normatively infer the maximal utility of the *a priori* information concerning a problem; i.e., every driver can equally perform such an inference. Since presumably all drivers share similar goals and resources, it is reasonable to believe that some drivers make good decisions while others make poor decisions.

From this normative view, variability in decision-making is not acceptable; there is only a unique decision that is correct. However, many cars are controlled by humans, and they do not use such representational systems to drive, nor do they use rational processes to decide and to act (Araújo et al., 2005; Hammond, 2007; Klein, 2001).

In contrast to this social-cognitivist approach, ecological dynamics analysis on interpersonal coordination is predicated on the concept of "shared affordances," rather than on the concept of shared knowledge (Araújo & Davids, 2016; Silva et al., 2013). Shared affordances are possibilities for action presented by the environment to a group of people perceptually attuned to them, thus rendering collective behavioral patterns feasible. The concept of affordance, which emerged from the ecological psychology of Gibson (1986), supposes direct perception, i.e., a tight functional fit between animal and environment without the need to invoke mental representations or further cognitive processes in order to perceive how the environment is meaningful for action. In fact, the environment is perceived in terms of how one can act in it.

Gibson (1986) criticized the notion of information within the computation paradigm, which considers that information is perceived indirectly; i.e., extra computation is needed within the brain to perceive the environment in order to (1) attribute meaning to meaningless stimuli; (2) decide how to act upon them and (3) program the movement to be executed by the body in response to those stimuli. In contrast, Gibson posits that action is intimately coupled with perception (e.g., individuals perceive action possibilities; perception is for action) because it depends on the direct detection (and use) of information such as patterns of surrounding energy (e.g., light or sound) (Gibson, 1986).

Relevant (meaningful) information can be perceived by the individual directly, without the need for representing the environment, or for attributing such representations to the meaningless stimuli that impinge on the senses, as proposed in the computational approach.

Gibson (1966) considered attention as a process for focusing on a circumscribed source of information. He explained that the "education of attention" is a gradual "attunement of perception" to the determining sources of information offered by the environment (Jacobs & Michaels, 2002; Cañal-Bruland et al., 2010; Shafizadeh et al., 2011).

The environment consists of patterns of energy distribution (e.g., light reflected by surfaces and objects) that specify relevant (meaningful) information (e.g., that the road is "drive-able") for an individual with certain abilities (e.g., a driver), thus offering specific opportunities for action (affordances; e.g., drive ahead). Moreover, as the individual is always interacting with the environment, there is no sense in separating cognition from perception and action. For instance, by studying visual perception, Lee (1976) identified an invariant in the optical flow (i.e., the pattern of light generated by a particular individual-environment circumstance, described in terms of a velocity vector field) dubbed as tau (τ), which was essential for the perception of time-to-contact, and was used by humans when performing interceptive actions.

Decision-making appears as an emergent process in the continuous interaction of an individual with certain abilities and the individual's surrounding environment, which in turn has particular affordances. Thus, decision-making can be conceived as a series of transitions in the course of action that emerge from the goal-directed process of selecting and acting on the affordances available in the performance environment (Araujo et al., 2006; Correia et al., 2012).

When referring to a group of persons doing activities together, rather than a single person, the notion of "shared affordances" is appropriate to explain coordination among group members. Key properties of the environment can be perceived directly, meaning that opportunities for action (affordances) are explicitly observable by different players in the same setting wherein they have been "trained to become perceptually attuned to them" (Silva et al., 2013, p.768). Consequently, players can present affordances to each other.

Numerous studies support the idea that humans can perceive very accurately another person's affordances. We can distinguish three possibilities that are vital in sport interactions: (1) affordances *for another person* or what others can do in specific situations (Ramenzoni, at al., 2008); (2) affordances *for joint action* (Richardson et al., 2007; Marsh, Richardson, & Schmidt, 2009) and (3) affordances *of another person* or what the other affords to us (Johnston et al., 2004). Correia et al. (2012) used virtual reality to research affordances on a 3 vs. 3 rugby task. A ball carrier wearing virtual reality goggles was supported by two virtual teammates running on the carrier's side and was confronted by a line of three virtual defenders. The researchers manipulated the program controlling the opponents to assign randomly to them actions to open gaps in the line as follows: Gap 1, in front of the carrier; Gap 2, close to the carrier; Gap 3, further on the line; and a no gap condition. Ball carriers responded with the action for the opening as follows: run in response to Gap1; short pass in response to Gap2; and long pass in response to Gap3. The researchers concluded that "…the action most often selected for each gap location was the affordance that best aligned with the task goal" (p.317). Importantly, more skilled players had the highest perceptual attunement to the relevant affordance. In summary, when training a particular collective task, individuals perceptually attune to the information that guides action to achieve individual and collective goals.

An Ecological Dynamics Approach to Driving Behavior in Roundabouts

A crucial affordance of the particular case of driving in a roundabout is whether a given gap in the traffic flow is pass-through-able (Warren & Whang, 1987; Wraga, 1999), or more correctly, drive-through-able. Thus, affordances are needed to guide the drivers' actions for entering the roundabout, for changing lanes inside the roundabout, and for exiting the roundabout.

Drive-through-able affordances are part of the "rich landscape of affordances" (Rietveld & Kiversten, 2014) of a driver. There is a rich landscape of shared affordances (e.g., affordance *of* others and as affordance *for* others) in a roundabout that are determined by the local characteristics of each roundabout. Such "shared affordances" can be "augmented" by signals (the indicator lights are the most commonly used but sometimes other signals including utterances, gestures, sounds, or honks are also utilized) communicating the intention of the driver (e.g., taking the next exit) in a way that ensures the message is clearly understood by other drivers. Thus, such signals act as informational constraints that help drivers direct their attention toward shared affordances which, according to each driver's action capabilities and intentions (Fajen et al., 2009), are used to coordinate their actions.

In the following two cases, we analyze the use of shared affordances to solve the local problem of collective driving in a roundabout.

Case 1: Canillejas roundabout, Madrid

In this clip, footage by a frontal camera reveals a situation of heavy traffic on a Friday night at rush hour in a roundabout located in Canillejas, north-east of Madrid city, Spain (see Figure 6).

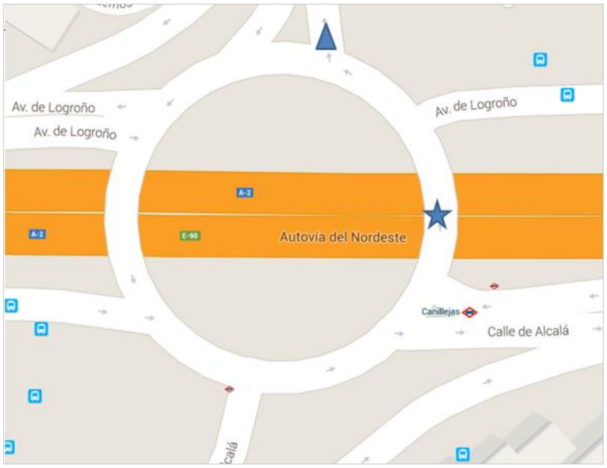

Figure 6. Roundabout in Canillejas (Madrid). The star marks the initial location of the analyzed cars and the triangle marks the exit of the roundabout in the clip. Adapted from Google Maps, https://www.google.com/maps/search/canillejas+roundabout+madrid/@40.4490826,-3.609463,17z

This clip shows how drivers can coordinate their actions in this situation of heavy traffic, even though they are not strictly following the driving rules. For instance, the black car, which is in a central lane trying to get into the next exit, had to signal for a long time to make clear to everyone around the driver's intention (Figure 7).

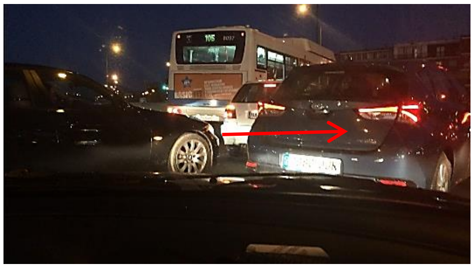

Figure 7. (0.16 s) The black car on the left starts signaling with the right indicator light to make clear the desire to exit the roundabout. Red arrow indicates the intended move of the black car.

It is important to notice that although traffic rules stipulate that cars exiting a roundabout should circulate on the right late, the black car in the footage is in one of the central lanes. The dense traffic, and in particular the blue car on the right, obstructs the black car's exiting action. During more than 20s the situation remains much the same. The cars advance gradually while making micro-adjustments to their trajectories (Figure 8). The back red lights constantly "on" in most cars indicate continuous breaking actions, which is necessary to maintain a minimal distance and thus avoid collision.

Figure 8. (0.39 s) The situation stays the same after 20 s.

The black car allows enough distance and timing for the blue car on the right to advance and open some space behind. At this precise moment, the drive-through-able affordance is perceived and exploited by the driver in the black car (Figure 9a, b, c).

In Figure 10, the black car proceeds to the exit before the green bus coming from the bottom right corner of the image closes the space again.


9a (1.01 s) **9b** (1.07 s) **9c** (1.08 s)

Figure 9a, 9b, 9c. The driver of the black car waits until a space is available and then uses it to cross two lanes and reach the exit. The solid red arrow indicates the intended move of the black car; the dotted arrow indicates the movement of the black car.

Figure 10. (1.09 s). The front part of a green bus (within the red dotted area) appears in the right, driving in the external lane of the roundabout, while the black car (red dotted arrow) is already taking the exit.

Such drive-through-able affordance is shared by every driver and it is plausible that the green bus on the right slowed down to leave the space open and hence allow the black car to pass through. Finally, as the traffic resumes, the green bus advances onto the external lane, which had become available after the black car exited the roundabout (Figure 11).

Figure 11. (1.12s). Traffic flow in the roundabout is maintained, the green bus advancing in the external lane.

Case 2: "La Dama Ibérica" Roundabout

In this case, footage by a frontal camera reveals a situation of heavy traffic in the roundabout known as "La Dama Ibérica," located in Valencia, Spain (see Figure 12).[4] Two motorbikes (weaker vehicles compared to cars) are able to navigate within a crowded roundabout by exploiting the drive-through-able affordance allowed at certain times by specific cars. Not only do the drivers of the motorbikes actively search their way through the cars; the drivers of the cars also actively allow space for the motorbikes to pass without delaying the overall traffic in this area of the roundabout.

In Figure 13, the two motorbikes enter the roundabout driving in the external lane. They are already signaling with their left indicator light. At that point, the signaling can mean two different things: On the one hand, they want to get into the central lanes of the roundabout; on the other hand, they are not taking the next exit, avoiding a possible collision with cars in the central lanes whose drivers would like to get this next exit. The disambiguation will be clearer as the driving continues.

Figure 12. Roundabout in Valencia. The star marks the initial location of the two motorbikes. The triangle marks their exit of the roundabout in the clip. Adapted from Google Maps, https://www.google.com/maps/@39.4902732,-0.4015359,17z

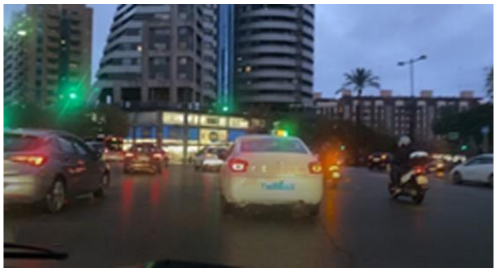

Figure 13. (0.14 s). Drivers of two motorbikes in the external lane signaling with their left indicator lights.

The motorbikes keep signaling to the left with the lights, which, at that point, clearly indicates they want to change to the central lanes. The white cab moves one lane to the left, the motorbike driver sees the drive-through-able affordance (Figure 14a) and occupies the empty space left by the cab (Figure 14b).

Figure 14a.

Figure 14b.

Figure 14a. (0.20 s). The white cab moves to the left land, and the motor biker starts moving too.
Figure 14b. (0.21 s) The motorbike moves to the center, occupying the empty space left.

The first motorbike exploits the open space left by the white cab to shift left and change lane again, yielding the space to the second motorbike, which changes one lane to the left to occupy the space left by the first motorbike (Figure 15a). As no other vehicle is blocking their advance, both change one more lane to the left (Figure 15b).

The second motorbike shifts again to the left lane, positioning itself in the back of the first motorbike, both proceeding to their chosen exit (Figure 16). Notice how the gap through which the motorbikes passed seconds ago has closed again (marked by the thick red line) so no drive-through-able affordance is available for any vehicle coming from the right lanes anymore.

Figure 15a.

Figure 15b.

Figure 15a. (0.25 s) Both motorbikes shift lanes to the left once.
Figure 15b. (0.27 s) The motorbikes shift lanes again.

Figure 16. (0.29 s) Both motorbikes proceeding to their chosen exit.

In this roundabout, the higher maneuverability of motorbikes and their smaller size in comparison to cars made drive-through-able affordance *of* others and *for* others easy to exploit for the concerted driving to proceed smooth and without delay. It was achieved even though motorbikes did not follow traffic rules strictly. According to the driving code, they should have stayed in the outer lane until they reached their chosen exit.

However, that would have implied a temporary blockage of the previous exit in which many cars were already queuing, resulting in unwanted delays and potentially risky situations. Thus, their partial non-adequation to rules was successful. It represented a practical local solution in which other cars also collaborated without apparent conflict.

Both cases (Canillejas and “La Dama Ibérica” roundabouts) illustrate how drivers can collectively generate a local solution to maintain traffic flow in a congested roundabout without disrupting the car flow too abruptly or causing an accident. This local solution required the coordination between drivers of different vehicles by perceiving and acting on a landscape of shared affordances. In the first clip (Canillejas roundabout), drive-through-able affordances *of* others as well as *for* others were exploited by the black car driver and green bus driver for finding an adequate timing of successful coordinated actions. In the second clip (“La Dama Ibérica” roundabout) drive-through-able affordances *of* others as well as *for* others were exploited by the two motorbikes and different cars in order to maintain the traffic flow without delays or potential crashes.

Implications

From the current standpoint of driverless car companies, the most optimistic future scenario to reduce traffic accidents and improve traffic flow seems to rely on completely replacing human drivers for autonomous self-driving cars. However, even if this process is ever achieved, the transition phase including both human-controlled cars and self-driving cars will last for some time. Thus, it is essential to predict the types of interactions that might occur between these drivers to avoid potential problems.

We emphasize here that, to our knowledge, no adequate attempt has been made to tackle this important issue. The current default assumption of the designer of self-driving cars is that the main challenge these cars will encounter is the unruly behavior of humans, who often do not comply with traffic rules. If every car, on every occasion, made rational decisions predicated by the traffic rules and the local information (including the goals of all the drivers), then we would reach a “driving heaven.”

In other words, the self-driving design rests on a representational model for decision-making and coordination that could take place only in closed systems (i.e., systems where all the solutions are known beforehand). However, as Hammond argued in his influential book *Human Judgment and Social Policy*, “[W]e live in a world of irreducible uncertainty, inevitable error, and unavoidable injustice” (Hammond,1996).

We believe the problem lies precisely at the core of this model’s assumption: Human drivers do not navigate according to such representational systems that imply *a priori* knowledge of the driving situation and traffic rules, and that allow decisions to be made before implementing the action. In reality, human drivers perceive opportunities for action (affordances) that can be perceived and acted-upon by other drivers (i.e., shared affordances) for navigating and coordinating driving actions between drivers. The occasion is its own “best model” (Brooks, 1991) by presenting the specific constraints and updated information as it evolves.

We cast doubts as to whether completely replacing human drivers for self-driving cars is the only, or even the most desirable, way to go—an opinion shared by users. Recent surveys cast doubts on users’ acceptance of full automation. The Gartner Consumer Trends in Automotive online survey (conducted in 2017 and polling 1,519 people in the U.S. and Germany), found that 55% of respondents will not consider riding in a fully autonomous vehicle, while 71% may consider riding in a partially autonomous vehicle (Gartner, 2017). Results from two recent opinion surveys of 54 and 187 U.S. adults showed that users were less accepting of high autonomy levels and displayed significantly lower intention to use highly autonomous vehicles (Hewitt et al., 2019).

We believe that self-driving cars present an impressive opportunity to develop a new type of technology aiming not towards replacing human drivers altogether but towards improving human interaction with the whole world. In order to do so, a theoretical rationale of how humans interact with the world is essential to achieve that goal.

The ecological dynamics framework considers that drivers are ecologically embedded agents, eager to integrate their activities within the increasingly complex technological envelopes in which they function (Araújo et al., 2006; Davids et al., 2012). These ideas conceptualize drivers as active organisms, with evolved tendencies toward mastering environmental challenges and integrating new experiences into a coherent form of life (Rietveld & Kiverstein, 2014), through continuous physical interactions in appropriately designed (driving) environments, which can be captured by ethnomethods (Garfinkel, 1967; Sánchez-García et al., 2016).

Possibly due to the western philosophical bias for considering the brain as so deeply special that it is distinct from the rest of natural order, there is a cultural tendency to develop technologies that assume minds as machines (but with more memory and processing capacities) (Pfeifer at al., 2011). Nonetheless, although the brain is an inherently dense, complex, and important organ for human behavior, it is only one part of a complex system that also includes the body and technologies, and which underpins human interactions with the environment when learning through driving activities.

In modern European societies, new waves of almost invisible, user-sensitive, semi-intelligent, knowledge-based electronics and software are poised to facilitate continuous interactions between drivers and their driving environments. However, a comprehensive theoretical framework to enhance the interactive relations between drivers as users and their knowledge-rich, responsive, digital environments is still lacking. A current challenge for designers, engineers, and psychologists is therefore to understand how drivers can successfully use available digital technologies to enhance success in driving (i.e., faster traffic and fewer accidents).

Ecological dynamics proposes that a driver's exploratory activities in a driving environment are predicated on the perception of affordances. This approach to behavior combines the advantages of agent-specific skills with the opportunities offered by a variety of environmentally distributed technological systems, thus providing a stream of useful contextual information to engage each driver in appropriate activities that enhance driving success.

This theoretical rationale proposes that each driver is a mobile locus of highly personalized resources who is engaged in driving supported by local, embedded computational devices. The driver is also a sort of automatic electronic trail-leaver whose movements and choices can be tracked by the devices with which the driver interacts. Affordances for interactions with technologies could enable each driver to identify as a member of a wide variety of drivers.

A theoretical framework such as ecological dynamics, or ecological psychology more generally, could be used for understanding how digital driving landscapes for drivers can be closely tailored to individual needs through their own driving activities. Research on driving design is needed to investigate how affordances can be geared to match emerging digital technologies in order to reduce accidents and improve traffic flow.

As we show in this study, settings such as roundabouts are of particular interest for investigating these topics because of the high number of interactions necessary to solve a problem of local order. Problems are solved slightly differently in each roundabout, depending on the structure of the roundabout, the traffic density, the skills of the drivers, the flow of incoming traffic, the driving culture of the country/city, among others.

We propose that roundabouts represent a perspicuous setting to study human drivers interacting with self-driving cars (and potential complications), as well as the different models addressing how collective driving action is guided. Future studies could address the following:

- The "driving style" or "driving culture" (habitual ways of driving in this specific setting) of each roundabout that constitute a "rich landscape of affordances" (Rietveld & Kiverstein, 2014) in order to understand local affordances and constraints.
- The collective behavioral patterns and their dynamics of the traffic flow in roundabouts (based on the previous point).
- The training of self-driving cars: According to Rosalie and Malone (2019, p. 164) the training in motor racing should include pre-event and simulator practice designed to replicate the task and environmental constraints of each session type to maximize the influence of drivers' preexisting skills. In order to train self-driving cars with human drivers in roundabouts, we could produce a realistic driving scenario featuring the same task and environmental constraints already identified in the two previous lines of study.

These suggested studies would give important insights into how human drivers and self-driving cars are guided by local information and how shared affordances are perceived by other drivers. Moreover, gaining a better understanding of these collective solutions for local problems evolving in real time in roundabouts would contribute to the commensurability of human and non-human drivers.

End Notes

1. According to the SAE (Society of Automotive Engineers) there are six levels of automation, ranging from fully manual to fully automated systems. Level 0 implies No Driving Automation; Level 1 implies Driver Assistance; Level 2 implies Partial Driving Automation; Level 3 implies Conditional Driving Automation; Level 4 implies High Driving Automation; and Level 5 implies Full Driving Automation (Hewitt et al., 2019, p.522). In this paper we refer to cars in level 5 of automation since levels 3 and 4 still demand that the human driver take control when on minor roads, a situation similar to roundabouts. Currently, there are no Level 4 autonomous vehicles for sale, though real-world testing started in 2020.
2. The most serious traffic incident, ending in the deadly crash of a Tesla model, occurred in January 2016, in China's Hubei province. Another fatal crash occurred on May 7, 2016, in Florida: The car's detection system mistook the white side of a turning trailer truck for the sky and drove directly into the side of the truck, passing under the truck and causing fatal injuries to the driver (Greenemeier, 2016). In March 2017, an Uber test vehicle was involved in a crash with no injuries in Arizona. The following year, March 2018, Elaine Herzberg became the first pedestrian to be killed by a self-driving car in the United States after being hit by an Uber vehicle.
3. "I use the term 'competence' to mean the claim that a collectivity member is entitled to exercise that he is capable of managing his everyday affairs without interference. That members can take such claims for granted I refer to by speaking of a person as a 'bona-fide' collectivity member." (Garfinkel, 1967, p.57, n.8).
4. Footage courtesy of Jorge Álvarez Delgado.

Authors' Declarations

The authors declare that there are no personal or financial conflicts of interest regarding the research in this article.

The authors declare that they conducted the research reported in this article in accordance with the Ethical Principles of the Journal of Expertise.

The authors declare that they are not able to make the dataset publicly available but are able to provide it upon request.

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References

Araújo, D. & Bourbousson, J. (2016). Theoretical perspectives on interpersonal coordination for team behaviour. In P. Passos, J. Y. Chow, & K. Davids (Eds.), *Interpersonal coordination and performance in social systems* (pp.126–139). London: Routledge.

Araújo, D., & Davids, K. (2016). Team synergies in sport: Theory and measures. *Frontiers in Psychology*. DOI: 10.3389/fpsyg.2016.01449

Araújo, D., Davids, K. and Hristovski, R. (2006). The ecological dynamics of decision making in sport, *Psychology of Sport and Exercise*, *7*(6), 653–676.

Araújo, D., Davids, K., & Serpa, S. (2005). An ecological approach to expertise effects in decision-making in a simulated sailing regatta. *Psychology of Sport and Exercise, 6*(6), 671–692.

AXA. (2016). Estudio circulación rotondas en

España. Centro de Estudios de Seguridad Vial.

Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence 47*, 139–159

Cannon-Bowers, J. A., Salas, E., & Converse, S. (1993). Shared mental models in expert team decision making. In J.J. Castellan (ed.), *Individual and group decision making.* Erlbaum: Hillsdale, NJ.

Cañal-Bruland, R., Kamp, J. V. D., Arkesteijn, M., Janssen, R., Kesteren, J. V., & Savelsbergh, G. (2010). Visual search behaviour in skilled field-hockey goalkeepers. *International Journal of Sport Psychology*, *41*(4), 327–339.

Correia, V., Araújo, D., Cummins, A., & Craig, C. M. (2012). Perceiving and acting upon spaces in a VR rugby task: expertise effects in affordance detection and task achievement. *Journal of Sport & Exercise Psychology*, *34*(3), 305–321.

Davids, K., Araújo D., Hristovski, R., Passos, P., & Chow, J.-Y. (2012). Ecological dynamics and motor learning design in sport. In A. M. Williams & N. Hodges (Eds.), *Skill acquisition in sport: Research, theory & practice, 2nd edition*, (pp. 112-130). London: Routledge.

DOT. 2016. “Secretary Foxx Unveils President Obama’s FY17 Budget Proposal of Nearly $4 Billion for Automated Vehicles and Announces DOT Initiatives to Accelerate Vehicle Safety Innovations.” (Retrieved from https://one.nhtsa.gov/About-NHTSA/PressReleases/dot_initiatives_accelerating_vehicle_safety_innovations_01142016).

Eccles, D. W., & Tenenbaum, G. (2004). Why an expert team is more than a team of experts: A social-cognitive conceptualization of team coordination and communication in sport. *Journal of Sport and Exercise Psychology*, *26*(4), 542–560.

Fajen, B. R., Riley, M. A., & Turvey, M. T. (2009). Information, affordances, and the control of action in sport. *International Journal of Sport Psychology*, *40*(1), 79.

Garfinkel, H. (1967). *Studies in ethnomethodology*. Prentice-Hall: Cambridge.

Gartner (2017). *Newsroom. Press Releases*, August 8. (Retrieved from https://www.gartner.com/en/newsroom/press-releases/2017-08-24-gartner-survey-reveals-55-percent-of-respondents-will-not-ride-in-a-fully-autonomous-vehicle).

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Massachusetts: Houghton-Mifflin.

Gibson, J.J (1986). *An ecological approach to visual perception*. New Jersey: LEA.

Gibson, J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile-driving. *The American Journal of Psychology*, *51*(3), 453–471.

Greenemeier, L. (2016). Deadly Tesla crash exposes confusion over automated driving. *Scientific American*, July 8. (Retrieved from http://www.scientificamerican.com/article/deadly-tesla-crash-exposes-confusion-over-automated-driving/).

Hammond, K. (1996). *Human judgment and social policy: Irreducible uncertainty, inevitable error, unavoidable injustice*. New York: Oxford University Press.

Hammond, K. (2007). *Beyond rationality: The search for wisdom in a troubled time.* New York: Oxford University Press.

Hewitt, C., Politis, I., Amanatidis, T., & Sarkar, A. (2019). Assessing public perception of self-driving cars. Proceedings of the 24th International Conference on Intelligent User Interfaces - IUI ’19. Marina del Ray, California — March 17 - 20, 2019, doi:10.1145/3301275.3302268

Jacobs, D. & Michaels, C. (2002). On the apparent paradox of learning and realism. *Ecological Psychology*, *14*, 127–139.

Johnston, L., Hudson, S. M., Richardson, M. J., Gunns, R. E., & Garner, M. (2004). Changing kinematics as a means of reducing vulnerability to attack. *Journal of Applied Social Psychology*, *34*, 514–537.

Klein, G. (2001). The fiction of optimization. In

G. Gigerenzer & R. Selten (Eds.), *Bounded rationality: The adaptive toolbox* (pp.103–121). Cambridge, MA: MIT Press.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, *5*, 437–459.

Levy, S. T., Peleg, R., Ofeck, E., Dubovi, I., Tabor, N., Bluestein, S. & Ben-Zur, H. (2016). TrafficJams: Social endeavors within a constrained responsive environment to investigate driving and traffic. In symposium: D. Abrahamson (chair), Discovery-based STEM learning 2.0: Are we there yet? The Annual meeting of the American Educational Research Association, April 8-12, 2016, Washington, D.C., USA.

Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social connection through joint action and interpersonal coordination. *Topics in Cognitive Science*, *1*(2), 320- 339.

Pfeifer, R., Bongard, J., & Berry, D.(2011). *Designing Intelligence: Why Brains Aren't Enough*. Berlin: GRIN Verlag.

Ramenzoni, V. C., Riley, M. A., Shockley, K., & Davis, T. (2008). An information-based approach to action understanding. *Cognition*, *106*(2), 1059–1070.

Richardson, M. J., Marsh, K. L., & Baron, R. M. (2007). Judging and actualizing intrapersonal and interpersonal affordances. *Journal of Experimental Psychology: Human Perception & Performance*, *33*, 845–859.

Rietveld, E., & Kiverstein, J. (2014). A rich landscape of affordances. *Ecological Psychology*, *26*(4), 325–352.

Rodríguez, J. I (2014). Cómo circular por una glorieta. *Tráfico y Seguridad Vial*, 228, 28-30 (Retrieved from http://www.dgt.es/revista/num228/#p=28)

Rosalie, S. M. & Malone, J. M. (2019). Do racing drivers practice racing? The effect of intentional following on formula car drivers' steering behavior. *Journal of Expertise*, *2*(3), 164–183.

Sánchez-García, R., Villaroya-Gil, Á., & Elrio-Lopez, A. (2016). Manipulating task constraints of situated normativity to study decision making in Krav Maga. *International Journal of Sport Psychology*, *47*(2), 133–154.

Shafizadeh, M., McMorris, T., & Sproule, J. (2011). Effect of different external attention of focus instruction on learning of golf putting skill. *Perceptual and Motor Skills*, *113*(2), 662–670.

Shafir, E., & LeBoeuf, R. (2002). Rationality. *Annual Review of Psychology*, *53*, 491–517.

Silva, P., Garganta, J., Araújo, D., Davids, K., & Aguiar, P. (2013). Shared knowledge or shared affordances? Insights from an ecological dynamics approach to team coordination in sports. *Sports Medicine*, *43*(9), 765–772.

Sleek, S., Michel, A. & Mikulak, A. (2016). Self-driving cars need social skills. Retrieved May 10, 2016, from the Association for Psychological Science, Observer website: http://www.psychologicalscience.org/index.php/news/motr/self-driving-cars-need-social-skills.html

Warren, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: Body-scaled information for affordances. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 371–383.

Wraga, M. (1999). The role of eye height in perceiving affordances and object dimensions. *Perception & Psychophysics*, *61*, 490–507.

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