Spatial navigation at the extremes: The collective accomplishment of high-speed, high-risk navigation in Rally Racing

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Abstract

Spatial navigation is a fundamental survival ability, and humans have evolved to navigate at the everyday scales of time and space that are experienced routinely. But some humans seem to shatter these limitations. Teams in the high-risk sport of rally racing must navigate complex courses at incredibly high speeds, where a single mistake can be fatal. How do rally teams accomplish navigation that is seemingly beyond the human scale? Here, we investigate rally racing to understand how distributed cognitive systems can accomplish spatial navigation at the extremes. By combining qualitative analysis, computer vision, and time series methods, we show how high-speed navigation is accomplished by a distributed system in which driver, co-driver, and cultural artifacts come into coordination. We end by discussing how extreme feats of cognition are made possible not by superhuman individuals, but by redistributing the computational burden across time, people, and artifacts.

Keywords: spatial navigation, distributed cognition, multimodal coordination, joint action, team cognition

Introduction

Imagine that you and a friend are driving slowly through a bustling city. You are using the GPS on your phone, looking around for familiar landmarks, discussing where to turn and when to stop, all while avoiding vehicles and pedestrians. On its own this is an incredible feat of joint action and coordinated spatial navigation, one that exemplifies how modern human navigation involves a clever combination of evolved spatial cognition, cultural practices, and cultural artifacts. Our basic abilities for navigating space have evolved over millions of years (Haun et al., 2010; O'Keefe & Nadel, 1978), and more recent cultural innovations now allow us to navigate through environments that are unfamiliar and complex.

Now imagine you are navigating at 120 mph on a narrow mountain road, on the edge of a cliff, with the engine screaming at 7,000 rpm. This is exactly what teams accomplish in the sport of rally racing, a high-stakes professional motorsport in which teams of two drive at top speeds in modified cars along long, winding routes that are unfamiliar and dangerous. Rally racing is an incredible feat of collective spatial cognition. But this form of spatial navigation seems to exceed the limits of what should be possible — to go beyond the "human scale" of scope and speed for which humans have evolved. The humans involved, however, are biologically ordinary. So how do they do it?

Spatial navigation on the "human scale"

Humans have evolved to navigate space at scales of time and space that are consistent with everyday experience. At this "human scale" of navigation, humans are skilled navigators (Gibson, 2014; Wolbers & Hegarty, 2010). We achieve this through dedicated neural machinery for keeping track of our location within the larger spatial environment. Grid cells in the entorhinal cortex provide a grid-like spatial triangulation system which updates as we move through the environment (Jacobs et al., 2013), while place cells in the hippocampus provide a context-dependent map of the environment (Ekstrom et al., 2003). This neural machinery allows us to develop internal cognitive maps of our spatial environment (O'Keefe & Nadel, 1978; Tolman, 1948), at least on the small-to-medium scales that characterize most human navigation.

Unlike our primate cousins, humans use cultural artifacts and practices to navigate. This has allowed humans to navigate more complicated spatial environments (Hutchins, 1995a). Magnetic compasses allow explorers to stay oriented in environments they have never encountered. Modern GPS systems allow people to navigate foreign cities without getting lost. These cultural tools allow humans to navigate successfully in the absence of prior familiarity.

Other cultural practices allow humans to navigate in ways that would seem impossible otherwise. London taxi drivers learn the city's complex array of streets by studying large static maps during an intensive training regimen (Griesbauer, 2022) — a regimen so grueling that it is associated with growth in the drivers' hippocampi (Maguire et al., 2000). Sailors of the Marshall islands can navigate over long distances in open waters thanks to "stick charts" made from string, knots, and sticks, which allow them to memorize complex patterns of ocean swells (Davenport, 1960). Other Micronesian sailors travel great distances in open waters thanks to a cultural practice in which they visualize the movement of an imagined island just beyond the horizon (Gladwin, 1970). In a wonderful example of cross-disciplinary research, anthropologist Edwin Hutchins and physicist Geoffrey Hinton teamed up to analyze how this practice enables Micronesian navigators to sail up to 150 miles between islands in open oceans (Hutchins & Hinton, 1984). With the right cultural tools and a sensitivity to multimodal cues in the environment, therefore, humans

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can navigate spatial environments that are larger and more complex than those we could navigate with our bare brains alone (Fernandez-Velasco & Spiers, 2024).

Pushing navigation beyond the "human scale"

All these examples of human spatial navigation, however, occur within a narrow band of speeds and timescales. When you have minutes for each decision, grid cells and stick charts may be sufficient for navigation. But what happens when we push beyond these human scales of speed and timing?

The sport of rally racing demonstrates what's possible. Rally race teams navigate complex terrains at speeds of 120 miles per hour (approximately 200 kilometers per hour). Often, teams will have only traversed the route once before the race, so they cannot rely on familiarity or habit. Some turns require split-second decisions that, if made incorrectly, can result in death — and, unfortunately, deaths do occur, earning rally racing a reputation as the world's most dangerous sport. This feat of spatial navigation, therefore, is right on the edge of human possibility. How do they do it? And what might this tell us more generally about the human capacity to move beyond our biological inheritance to accomplish extreme feats of cognition?

We consider two possible ways in which rally race teams accomplish their apparently superhuman feats of high-speed spatial navigation. First, they may indeed be superhuman, in that they represent extreme outliers in key abilities such as motor control and interpersonal coordination. Alternatively, they may be all too human — rally racing is, after all, a deadly sport — but their human abilities are organized by culture to create a distributed navigation system with properties that differ from those of any individual (Anderson, 1972).

This second approach — adopting a unit of analysis that goes beyond the individual — has been fruitful for investigations within cognitive science of other extreme feats of human cognition (Hutchins, 1995a, 1995b; van Eijndhoven et al., 2023; Spivey, 2024). Commercial airline pilots, for instance, must keep track of a variety of speeds and wing configurations that would tax the memory capacities of any individual, even a highly trained one. But a classic analysis by Hutchins (1995b) revealed that the task of remembering was accomplished not by any one individual but by the broader sociotechnical system of the cockpit — a system that included two pilots and a variety of external representations, with information flowing in a coordinated way through the system. Similar analyses have shed light on how teams can solve complex problems that would overwhelm an individual working alone (van Eijndhoven et al., 2023; Spivey, 2024). A key take-away from these studies is that the collective *assembly* of a system is often as important as the system's *components*. Exceptional feats of human cognition are often accomplished by distributed systems with system-level capabilities that are more than the sum of the system's parts.

The current study

Here, we show how a systems-level perspective can make sense of the extreme feats of spatial navigation accomplished by rally racers. Part I offers a qualitative analysis of the distributed system that accomplishes rally race navigation. We describe how the driver, co-driver, a cryptic shorthand script known as 'pace notes,' and the car itself function together as an integrated cognitive system during a rally race. In particular, we describe how these heterogeneous components are brought in and out of coordination in order to accomplish navigation. Part II uses computer vision and time series analyses to quantify the timescale of this process of coordination. We find that the multimodal coupling between driver and co-driver is no faster than everyday interpersonal interaction; the driver and co-driver are not superhuman coordinators. Instead, the rally system involves mundane parts combined in clever ways to give rise to an exceptional collective accomplishment. We end by discussing implications for the cultural accomplishment of extreme human cognition.

Part I: The distributed cognitive system of rally race navigation

To start, we offer a high-level description of the rally race system. We identify the system's components, describe the information encoded in each component, and discuss how information propagates through the system. Our analysis here is based in part on a video corpus we assembled of professional rally teams, consisting mostly of in-car race footage. Rally race navigation poses a computational problem that seems to exceed the real-time capacities of any individual human: computing safe trajectories through unfamiliar terrain at high speeds, where safe trajectories require millisecond-scale corrections. Ultimately, we show how extreme-speed navigation is accomplished by distributing the burden of information processing across space and time.

Bounding the system

Unlike circuit racing (e.g. Formula 1), rally racing unfolds over long, complex, and unfamiliar routes, with blind corners and uneven terrain. Teams have limited opportunities to practice and memorize each course. As a result, on race day, teams are faced with a repeated challenge: deciding how to attack each corner — that is, how to balance safety and speed at each turn. Winning the race (and surviving) comes down to small variations in angle of approach, speed, gear selection, braking, and throttle.

Each corner of the course poses its own set of problems that must be resolved on the order of milliseconds — well beyond the everyday human scale of spatial navigation. This is far too quick to rely on an internal spatial representation of the course, no matter how rich it may be.

As we unpack below, the solution to this challenge is that the relevant knowledge is not limited and localized to the driver's head. The task is accomplished by distributing the cognitive workload across the driver, co-driver, pace notes, and vehicle.

The rally race system's components

The *driver* is positioned behind the wheel. They engage in constant pattern recognition based on the visual information streaming through the windshield: the road ahead, visual cues for where to position the car before approaching each corner, and obstacles like large rocks, other vehicles, or pedestrians. They listen to speech from the co-driver, who signals upcoming corners. The driver handles the steering, brake pedal, hand brake, and throttle inputs to the vehicle[1]. Controlled studies of race car drivers suggest that while their performance is highly skilled, it does not rely on exceptional reaction times or motor control (Lappi, 2018). While impressive, expert drivers are within the normal range of human performance; the best drivers are able to perform at a high level thanks to a combination of highly trained perceptual abilities, a vast body of knowledge, and top-down cognitive processes (Lappi, 2018).

The *co-driver*, sometimes referred to as the navigator, sits in the passenger seat and provides information in speech about the route ahead. Throughout the race, they read so-called `pace notes' from a paper notebook in their hands, coordinating the delivery of each note with the driver's steering and the car's position on the course. (While the co-driver's primary purpose during the race itself is to deliver the pace notes, they also coordinate race logistics, provide emotional support, and can even step in as an on-the-fly mechanic.)

The *pace notes* are handwritten notes in a physical notebook held by the co-driver. They contain information about the entire course, including the severity of each corner and any potential obstacles (Fig. 1A). These notes are constructed before the race, usually a day or two beforehand, during a drive known as a *recce* (short for reconnaissance). During this reconnaissance phase, the driver and co-driver will slowly navigate the course (typically at 20% of the race day speed), taking notes on each turn and hazard along the way. If for instance a corner is considered "low severity" because the road is open or flat, and if the turn veers to the right, then the pace note might be '5 right.' The number indicates the severity of the turn and corresponds roughly to the gear the driver should be in before entering the corner (Fig. 1B). If the same corner were on the downward side of a hill, the co-driver might add 'hold over crest' to signal to the driver that they should wait until after the hill before accelerating, because otherwise the vehicle might destabilize. If there were a large rock at the inner edge of the corner's apex, the note might further include 'don't cut' to indicate to the driver that they should not drive too close to the road's inner edge. These notes are compressed in a coded language that is partially conventionalized — with shared features across the racing tradition — but also idiosyncratic to each team.

These notes function as a shared mental model of the course. Critically, this model is *precomputed* (Hutchins, 1995a) before the actual race. In this way the most demanding aspects of spatial reasoning are displaced in time and distributed between driver and co-driver, thus shifting the burden of spatial reasoning from the race itself to a prior phase of deliberate collaboration.

The *vehicle* itself is a rich source of information. The driver controls the car using the steering wheel, throttle, and brakes, but these car components also offer nearly instantaneous feedback to the driver, as do a variety of gauges and even the seat. Resistance and vibrations travel through the steering wheel to the driver's hands, carrying information about what is going on in the vehicle's front wheels. The seats' vibrations provide information about how much traction there is in the vehicle's rear wheels. The driver must combine this stream of information with the co-driver's spoken pace notes to decide whether the current course of action is likely to succeed.

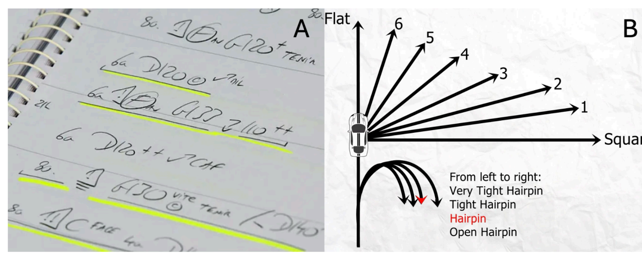

Fig. 1. Pace Notes. (A) Image of a team's actual pace notes. (B) A conventional coding system for turn severity.

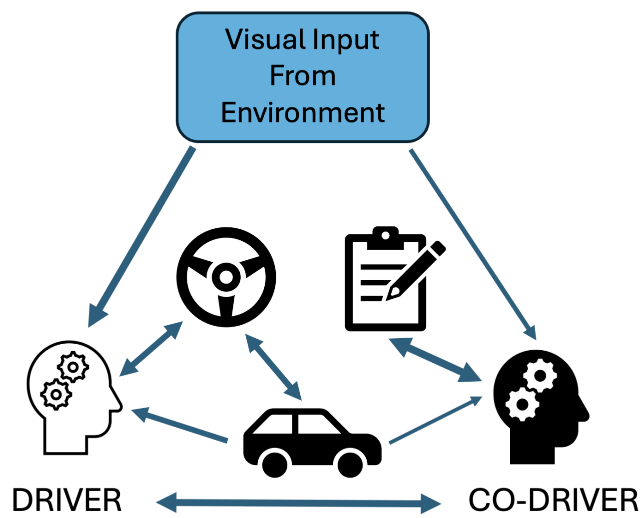

Fig. 2. Information flow in the rally system: A schematized network diagram of how information moves through the rally system. Arrows indicate the direction of propagation, from source to receiver. Line weights indicate bandwidth of information flow.

[1] The co-driver can, on occasion, intervene directly on the vehicle, for instance by pulling the hand brake.

How information moves through the system

Information propagates rapidly and constantly through this system (Fig. 2). As information propagates through the system, it transforms in ways that reduce the computational burden faced by the driver.

A key component of this cascade of information is *precomputation*: the construction in advance of representations that transform how a task can be accomplished in the moment (Hutchins, 1995a). In rally racing, pace notes are precomputed during the recce, often collaboratively, redistributing and front-loading the computational burden of spatial reasoning across time and between the driver and co-driver. The driver's task is thus transformed from reasoning on the fly about the car's high-speed trajectory to a far simpler and faster one: pattern-matching between visual input and the co-driver's spoken pace notes. As a consequence, the task faced by the driver is well calibrated to their evolved abilities for pattern recognition and multimodal integration.

To appreciate the computational burden faced by this navigational team, consider the flow of information during a single hypothetical corner. As the car exits one corner and prepares for the next, visual information about the road ahead streams in through the windshield. The co-driver, moving their finger from the previous pace note to the next, looks for the right time to communicate about the upcoming corner. When they decide the time is right, they read the next note aloud: "crest into right four tightens." Here, "crest" signals that the car will go over a hill (which conveys to the driver that the car may lose traction as the weight becomes unsprung), "right four" signals a medium-sharp right turn (Fig. 1B), and "tightens" signals that the corner has a decreasing radius and becomes sharper partway through. The co-driver thus uses real-time visual cues to time their access to precomputed information about the next corner, and then transforms this information from one modality (written) into another (spoken). The driver must then integrate this spoken pace note with visual input from the road and vibrations from the steering wheel and seat, in order to initiate a series of motor actions: shifting into the appropriate gear, braking to the appropriate speed, moving the steering wheel to the correct orientation. As the vehicle responds to the driver's actions, it transmits instantaneous information to the driver and co-driver's bodies about momentum, traction, and yaw angle. A new turn approaches, the co-driver shifts their finger to the next note, and the entire cycle repeats.

This stylized description illustrates how information transforms as it propagates between the systems' components. Information about how to attack each corner is distributed throughout the system, often arriving just in time for the driver's decision. No single component maintains a complete representation of the corner's geometry. Individual humans are engaged in simple pattern matching and basic motor actions. When completed in the right sequence, however, the system as a whole is able to fly around corners at just the right speed.

If extreme navigation is made possible by precomputing information about the course, then the interpersonal coordination between driver and co-driver need not involve some kind of superhuman, millisecond scale coupling. Instead, their coupling may resemble much more mundane instances of dyadic coupling, such as turn-taking in conversation, which unfold on the timescale of seconds rather than milliseconds (Stivers et al., 2009). We test this prediction in the next section.

Part II: Quantifying driver-navigator coordination during high-stakes, high-speed navigation

To quantify the timescale of interpersonal coordination, we focus on two continuous signals: the driver's steering and the co-driver's speech. As an initial proof of concept, we focus on one of the most iconic teams, Ari Vatanen and Terry Harryman, from a "golden era" of racing known as the Group B era[2], competing at one of the most notorious and dangerous races, the Manx International Rally.

Methods

Data

Multiple time series were extracted from a videorecording (N = 1) filmed in 1983 at 25 frames per second using an on-board camera mounted to the rollcage of a car cockpit. The video is publicly available (YouTube, 2013).

We focus on a critical segment of the entire race footage (51.6 seconds). We selected this particular segment because it illustrates both the sport's stakes and the team's incredible skill: the driver loses control and nearly crashes but handily escapes death (around 2:00 minutes into the original video and 0:42 seconds into the segmented clip).

Extracting a time series of driver steering

To extract a time series of the driver's steering, we used DeepLabCut (Mathis et al., 2018), a computer vision framework for pose estimation using a pre-trained deep neural network. We used DeepLabCut to retrain the vision model on key landmarks within the car cockpit, including: the driver's left and right hands, the steering wheel's spokes, the shift knob, and a corner of the co-driver's notebook (Fig. 3). This generated a frame-by-frame time series of the x,y coordinates of each of the tracked landmarks. We then calculated the steering wheel angle in each frame of the video using the center of the steering wheel and points along spokes of the steering wheel. As a continuous measure of driver activity, we calculated the absolute value of frame-to-frame wheel angle change.

[2] This "golden era" of rally racing (1982-1986) was notoriously dangerous due to its lack of horsepower restrictions, safety standards, and crowd control.

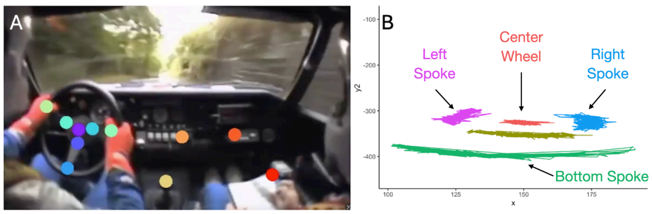

Fig. 3. Computer vision tracking of key landmarks within the car cockpit (A) Cockpit view, with landmarks of interest identified by the DeepLabCut deep neural network. (B) Location over time of five key landmarks: center of the steering wheel (orange/1), left spoke (purple/5), right spoke (blue/4), bottom spoke (gold/2), and far bottom spoke (green/3). Location along the x- and y-axes indicate the landmark's position in the video frame. (Colors in panel A do not correspond to colors in panel B.)

Extracting a time series of co-driver speech

To extract a time series of the co-driver's speech, we isolated the co-driver's speech from the video's audio. To isolate the co-driver's speech, we used CapCut, an AI-powered video editing toolbox (ByteDance, 2025). As a continuous measure of co-driver pace note delivery, we calculated the proportion of time that he was speaking in a sliding window of 1 second.

Results

Driver and co-driver were consistently active (Fig. 4). In the time series of steering wheel angle changes, large values indicate counter-steering performed to maintain the vehicle's balance. Note the extremely large spike at 42 seconds, when the vehicle nearly crashes and the co-driver mutters in horror, "oh dear god."

To identify the timescale at which driver and co-driver were coordinating their joint activity, we calculated the cross-correlation of the driver's steering and the co-driver's speech (Fig. 5). To do so, we calculated the cross correlation function, CCF(k), for lags k of up to four seconds. The driver's steering wheel adjustments were not correlated at all with the co-driver's simultaneous speech (i.e., at lag $k = 0$), nor was it correlated at short lags. Instead, the driver's steering wheel adjustments were correlated with the rate of the co-driver's speech at lags of approximately one to three seconds (i.e., 25 to 75 frames). Note that the lagged cross-correlation was significant at positive and negative lags, indicating that the co-driver's speech predicted the driver's steering wheel adjustments a few seconds later, and conversely the driver's steering wheel adjustments predicted the co-driver's speech a few seconds after that. Critically, this interpersonal coordination between driver and co-driver unfolded on timescales that are not exceptional for human interaction. Rather than coordinating on the timescale of milliseconds, driver and co-driver are coupling their steering and speech on timescales consistent with ordinary patterns of joint action and communication (e.g., turn-taking, Stivers et al, 2009).

Finally, to quantify the information flow from co-driver to driver, we conducted a Granger causality analysis. Granger causality is a statistical method for quantifying the directional flow of information from one process to another (Granger, 1969). We used a lag of 1.5 seconds (36 frames), which corresponds to an interactional timescale at which spoken instruction could plausibly influence coordinated action, as suggested by studies of conversational turn-taking (Stivers et al., 2009). This analysis confirmed that co-driver speech predicted the driver's future steering wheel adjustments ($\beta = 0.11$, $p < .001$), above and beyond the driver's past steering wheel adjustments. As with all Granger analyses, these results reflect predictive structure and not necessarily mechanistic causation.

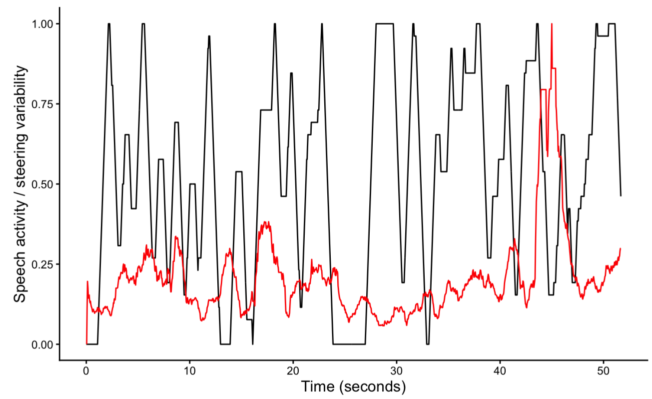

Fig. 4. Time series of driver steering and co-driver speech. The lines show the proportion of co-driver speech in a one-second sliding window (black) and the absolute value of steering angle change (red). For comparison, we have normalized each time series so it ranged from 0 to 1.

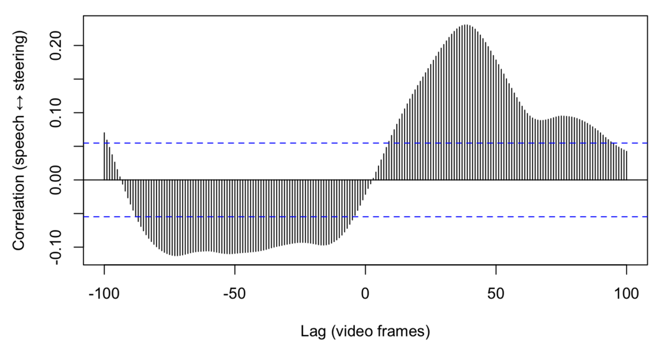

Fig. 5. Cross-correlation of driver steering and co-driver speech. The lag (x-axis) is in video frames; 25 frames correspond to one second. Positive [negative] lags compare changes in the steering wheel angle to later [earlier] speech. (Dashed blue lines = 95% confidence intervals; values outside these bounds are statistically significant.)

Discussion

Rally race teams accomplish exceptional feats of spatial navigation, but not because the participants are superhuman.

Our qualitative analysis of a rally race team identified key components that represent information about the navigation task. The star of this assemblage is the pace notes that the team prepares ahead of the race, and which the co-driver reads aloud during the race itself. These pace notes are a written record of the team's precomputed solutions to the puzzle posed by the route's sequence of turns.

Critically, for these notes to help the driver, they must be delivered at carefully timed intervals. Our quantitative analysis demonstrated the timescale on which these notes are coordinated with the driver's steering. The co-driver's speech and the driver's steering were not coordinated on the millisecond timescale that one might have assumed if the temporal dynamics of the whole car were due to the super-rapid coupling of its two human components. Instead, co-driver speech and driver steering were coordinated on the timescale of seconds. Interpersonal coordination within the car, therefore, is not superhuman. It's the distributed system as a whole, with its information processing distributed across space and time, that can accomplish superhuman feats of navigation.

The coupling between driver and co-driver was bidirectional. It makes sense that the co-driver's speech would affect the driver's subsequent steering; that is, after all, the purpose of the pace notes. But the coupling went in the other direction, too. Just as the driver is adapting their steering inputs to the co-driver's pace notes, so too does the co-driver adapt their speech to the driver's steering. One can imagine how the co-driver, having witnessed multiple quick adjustments to steering, might decide to hold off on new pace notes until the driver has stabilized the vehicle.

Our quantitative findings focused on a single iconic team ($N = 1$) and a brief segment of footage (51.6s); future work should examine whether these coordination dynamics generalize across other teams, races, and levels of expertise. Moreover, our measure of co-driver speech is coarse-grained; future work should include measures that capture the semantic content of the pace notes.

Combining pattern recognition and external representations to unlock cognitive capacities

This analysis of rally racing highlights a recurring strategy by which humans have unlocked new cognitive abilities. Humans evolved strong abilities for pattern recognition, modeling the world, and manipulating the environment — key skills for using external representations as part of our thought process (Rumelhart et al., 1986). When those external representations contain solutions to problems, we can leverage our pattern-recognition abilities to recognize the solution with in-depth, skull-internal processing. This is the secret behind much of the cultural machinery of mathematics, such as algebraic notations (Rumelhart et al., 1986; Hutchins, 1995a; Goldstone et al., 2017).

Here, we've shown how a similar strategy is used by rally race teams to solve high-stakes spatial problems at top speed. The driver and co-driver precompute the solution for each corner of the route, so that the task faced by the team during the race isn't to determine on the spot the best way to navigate each corner. The driver doesn't even need to maintain a rich cognitive map of the environment. Instead, the driver can simply integrate multimodal cues from the course and the co-driver's speech to match each corner to its precomputed solution. What would have been an insurmountable reasoning task is transformed into a far simpler pattern-matching task.

Does extreme spatial navigation create interpersonal "synergies"?

One possible line of future research could explore the analogy between expert rally systems and skilled motor action. Just as joints and muscles are coordinated as motor synergies during skilled action (Bernstein, 1967), we suspect that expert rally teams may function as *interpersonal synergies*: coordinated systems in which component parts mutually constrain one another to reduce the system's complexity (Riley et al., 2011; Fusaroli et al., 2014).

If rally teams do form interpersonal synergies, several properties should be evident in the coordination of their component parts. First, the system's components should adjust and coordinate with each other to preserve the system's overall function. Second, coordination should be efficient and adaptive: components should couple together tightly when rapid information transfer is needed, yet remain capable of looser coupling in order to make adaptive responses to unexpected perturbations. Third, synergistic coordination should reduce the system's dimensionality, with mutual constraints among the parts causing a reduction in unnecessary variance. Rally teams may accomplish their collective computations by acting as synergistic systems, and the most successful teams may be especially synergistic.

Conclusion

Rally racing offers an opportunity to understand how enculturated humans can accomplish feats that seem to lie beyond the limits of human potential. Rally race teams accomplish extreme spatial navigation not by accelerating human cognition, but by reorganizing when, where, and how cognition occurs. Rather than relying on rich internal models of the spatial environment, the driver, co-driver, and cultural artifacts (pace notes and vehicle) come into coordination to transform this incredible computational feat into a more tractable one. Our qualitative analysis showed how spatial knowledge is precomputed, transformed, and propagated across heterogeneous system components. Our quantitative analysis revealed human-scale bidirectional coupling between driver and co-driver. These findings offer a solution to how humans exceed their biological constraints: by distributing cognition in clever ways across people, artifacts, and practices.

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