Trends in
Cognitive Sciences

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Review

Wayfinding across ocean and tundra: what traditional cultures teach us about navigation

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Research on human navigation by psychologists and neuroscientists has come mainly from a limited range of environments and participants inhabiting western countries. By contrast, numerous anthropological accounts illustrate the diverse ways in which cultures adapt to their surrounding environment to navigate. Here, we provide an overview of these studies and relate them to cognitive science research. The diversity of cues in traditional navigation is much higher and multimodal compared with navigation experiments in the laboratory. It typically involves an integrated system of methods, drawing on a detailed understanding of the environmental cues, specific tools, and forms part of a broader cultural system. We highlight recent methodological developments for measuring navigation skill and modelling behaviour that will aid future research into how culture and environment shape human navigation.

Highlights

Studies of navigation in traditional cultures are reviewed and key insights provided.

Traditional navigation methods often rely on deep understanding of patterns in the environment combined with physical artefacts that aid learning and dissemination of knowledge.

The diverse elements involved in a navigational process all operate within a larger interrelated information system that is adapted to the local environment.

Novel methods for data analysis and modelling provide new opportunities for understanding how culture and environment shape navigation skill.

The diversity of human navigation

Finding his way in the Yukon Flats of northern Alaska, the Gwich'in Elder Paul Herbert uses an unusual strategy. He looks at the night sky and projects different stars onto attributes of the mythical fox-like creature *Yahdii*. The stars form the tail, leg, or snout of *Yahdii,* each pointing to different regions of the flatlands, guiding the traveller when no path or landmarks are available [1].

The Gwich'in celestial scheme is paradigmatic of most traditional navigation in that it is both local and inseparable from a larger cultural system: to use it one must learn particular constellations, placenames, and mythology. Using such systems, humans show remarkable feats of navigation across a variety of environments, from trekking dense tundra, to sailing vast oceans, to negotiating the streets of sprawling cities. Humans exploit a rich diversity of strategies to achieve this. While experimental research in the laboratory has helped uncover the cognitive features and brain systems underlying navigation [2,3], most studies test western participants in highly controlled settings and, thus, ignore the heterogeneity of cultures and environments that humans navigate.

Laboratory-based studies of human navigation have taught us much about the different strategies used, existing biases, and the impact of demographic factors on navigation ability [2,4,5]. In particular, virtual reality (VR) has proved a useful tool to manipulate environments and provide insight into the neural basis of navigation [2,6–8]. In parallel, a variety of studies have examined real-world navigation experience, often with university students navigating local terrain [9–14]. Such empirical studies have helped reveal the different forms that navigation can take (**wayfinding**/**path integration**; see Glossary), reference frame use (**egocentric**/**allocentric**), different strategies used (**map based**/ **landmark oriented**), and the engagement of different brain regions [2,15]. However, the environments used often require a limited range and the participants are often university students. While many cognitive scientists will have encountered descriptions of exceptional navigators who use traditional techniques, such descriptions are rarely presented in a way that allows for integration with their research. Here, we seek to aid such integration.

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In this review, we shine a light on the variability of navigation worldwide and explore the ways in which cultures flexibly adapt to diverse environments. We explore existing anthropological research of traditional navigation in indigenous communities, as well as ethnographic studies of navigational traditions in subcultures within western societies, such as taxi drivers. Navigating a city, forest, or ocean using traditional methods will place different demands on the navigator. Studies show that different communities have developed idiosyncratic methods for solving the navigational challenges posed by their environments [1,16–19]. We conceptually organise these strategies by focussing on key aspects of navigational culture, including environmental cues, **systematised knowledge**, visualisation techniques, and cognitive artefacts, across 49 populations in 30 nations. The resulting picture is one of navigation situated in its terrain, involving a multitude of interrelated elements. Finally, we discuss recent methodological developments enabling researchers to integrate the study of traditional navigation with laboratory-based approaches.

The understanding of navigation that emerges through our review departs from the classical understanding in psychology in several ways. First, navigational strategies are dictated by the habitual environment encountered. In contrast to laboratory studies, the importance and interaction of environment and culture are central to anthropological literature. Second, laboratory studies of navigation generally focus solely on visual cues, often because of the need for concomitant neural recording (although many early studies involved real-world navigation; e.g., [20]). Here, we show how, in a range of cultures, different sensory modalities serve to direct the navigator to relevant environmental information to overcome local orientational challenges. There is also a general tendency to equate navigational mastery with the command of spatial information in allocentric frames of reference, but we show that, in some cases, navigational experts rely instead on egocentric frames of reference together with heuristic techniques that are adapted to particular environments [21]. Across many cultures, we find the exploitation of agent–environment regularities, and how both portable and durable tools enhance the cognitive abilities of navigators, but neither internal nor external resources can be understood without reference to the larger system in which they are embedded. All of the elements of a navigational culture are shown to work only when they operate within a larger interrelated information system that is adapted to the local environment [17,22].

A key to success: combining multimodal environmental cues

The islands of the western Pacific contain arguably some of the most impressive navigators on our planet. They have to be. Navigational errors in the open ocean can be fatal. Anthropological research has explored the traditional navigation skills of sailing cultures all across the Pacific [23]. We look first at sailing methods in the Marshall Islands (Figure 1). Traditional sea navigation in the Marshall Islands relies on wave piloting [24]. Navigators guide their canoes by reference to changes in swell and current patterns, which they use to determine the location of faraway islands. During training, this embodied knowledge is combined with learning from ‘stick charts’, made from coconut strips and cowrie shells, which model wave concepts and interrelate locations of known wave patterns, with shells indicating the location of atolls [24]. At sea, navigators decide on an initial course based on their knowledge of the configuration of islands, and then use changes in the rhythmic motion of the canoe to sense the transformation of wave patterns [22]. For the Marshallese, the understanding of wave patterns is a form of practical knowledge. While there is a linguistic element to the learning and naming of wave patterns, describing the process is a challenge because feeling the waves is primarily **action oriented** [25].

The use of environmental cues in a way that adapts to local orientational challenges is a recurrent theme across cultures. Pacific Ocean navigators of different island cultures report using stars [23] and oceanic lights (such as *telapa*, a lighting-like flash on the surface of the water reported by the Taumako Islanders in the Solomon islands) to aid navigation and reorientation [17]. Importantly,

Glossary

Action-oriented knowledge: knowledge that defies linguistic expression. An example is the kinaesthetic knowledge of the motion of a canoe, which is hard to put into words. Action-oriented knowledge is widespread in navigational culture, and poses a problem for cognitive anthropology, which has traditionally relied on language as a means to access people's cognitive processes.

Allocentric reference frame: spatial representation in which the locations of objects are not coded in relation to the observer but in relation to other objects and to global landmarks (e.g., where the table is relative to the couch, or where the local museum is relative to the North).

Durable media: transformations of the environment that can aid navigation, but that only work within their original emplacement. Examples are certain forms of rock art that contain not only geographic information about the surrounding environment, but also signage, trail-breaking, or trail-marking.

Egocentric reference frame: spatial representation in which the locations of objects are coded in relation to the observer (e.g., where the table is relative to my viewpoint, such as left)

Information systems: structures for the organised transmission of information, in which different elements are interrelated. The information systems aiding navigation encompass internal representations, shared bodies of knowledge, and material structures. The alignment of these interrelated elements within the environment is what makes navigation possible.

Landmark-oriented strategy: an approach to wayfinding in which the agent relies on visible and distinct objects and features in the environment (landmarks), and then uses remembered routes between those objects to find their way to a destination.

Map-based strategy: an approach to wayfinding in which the agent relies on an internal, allocentric representation of an environment (a cognitive map), and then uses that representation to infer their position and find their way to a destination. It is important to clarify that the focus here is on human spatial navigation, while the core ideas about cognitive maps were developed in freely moving rodents confined to laboratory spaces [123–125].

such traditional navigators do not simply rely on one feature alone; they combine these features with other cues, such as wind directions, stars, currents, and swell patterns [17]. When we shift to terrestrial navigation, determining direction can be achieved in a range of ways (Table 1). In some territories, there is an overall general inclination, so slope can be used as an orientational cue, as used by the Tenejapan Tzeltal [26]; this is also a known strategy among Nova Scotia deer hunters [27]. Different Inuit groups are famous for using the direction of the wind to maintain a given orientation, and cloud formations, sea waves, and animal behaviour can all be used to infer incoming shifts in the wind [28]. Snowdrift patterns can point in particular directions, which is especially useful while navigating large extensions of flat tundra or during periods of poor visibility [29].

A key observation across studies is the impressive multimodal nature of the cues used and their selection dependent on the environment. The waves in Marshallese navigation are primarily proprioceptive/vestibular cues, and the wind is primarily a haptic/auditory cue [22]. For the Batek people in the rainforest of Malaysia, auditory cues (e.g., birdsong) can be sensory markers of particular places [30]. The rainforest is visually impenetrable after a few metres; thus, interpreting auditory cues becomes crucial, because the surrounding soundscape becomes a source of information of potential dangers [30]. Olfactory cues can also serve as sensory markers and to signal broader ecological events. For Hawaiians in Nuʻalolo Kai, nuanced shifts in smell correspond to the ebb and flow of the tide [31], and the Pitjantjatjara people of Australia have olfactory associations for particular landscapes, which change seasonally [32].

In sum, given that traditional navigation involves navigating diverse natural environments, the navigators have developed a variety of strategies. Cues come from different modalities, and many types of cue are used in an adaptive way. There is considerable variability in the informational structure of each environment; thus, being able to use cues for orientation requires enculturation and training [17,22,23]. While experimental psychology has largely focussed on clearly distinguishable visual landmarks [33,34], anthropological fieldwork shows the diversity of cues that people can use to navigate, and the role of culture in mediating their use.

Systematised knowledge

On our journey westward, we consider the value that organising knowledge into a holistic system brings the traditional navigator. We begin with a focus on the culture of the Evenki. Evenki people are traditionally reindeer herders and, even among Siberian indigenous groups, are renowned for their wayfinding and hunting talents [35]. At the heart of the Evenki spatial and social organisation is their knowledge of river systems. During travel, rivers serve as landmarks, routes, and boundaries. The Evenki always set camp by a river and, when hunting, they will wander after prey over an area within two rivers, which partition the taiga into regions. Once the hunting is done, they can again use the rivers to get back to camp, which turns a complex 2D problem into a 1D problem [35].

The Evenki hydrological schema is a clear example of how local systematised knowledge organises wayfinding behaviour. Importantly, knowledge of rivers is intertwined with other systematic knowledge of land types, most clearly in their well-documented **toponymic system**, a typology of landscape that hunters can use to make navigational inferences (e.g., the type of landscape denotes its position in a river system), which can lead them to rivers [19] (see Box 1 for the interplay between language and spatial cognition). There is a tendency to frame traditional ecological knowledge as practical or procedural in nature [36]; that is, as 'knowledge how', in contrast to the 'knowledge that' characteristic of western science. What the typology of landscape of the Evenki shows is that traditional ecological knowledge is also conceptual and theoretical. It spans both knowing that and knowing how, and both deductive and inductive reasoning (i.e., it is based

Naturefacts: naturally occurring structures and objects systematically exploited for human cognitive processes (e.g., using a seashell as a musical instrument). These lie on the continuum between artifacts and naturally occurring structures, and are particularly useful for navigation. Rather than a category of their own, the very idea of naturefacts perhaps highlights the many borderline cases between the direct physical transformation of the environment (e.g., rock art) and the cultural transformation of the environment (e.g., the reading of cardinal directions out of snowdrift patterns).
Path integration: ability to keep track of relative position and orientation on the basis of self-motion information, such as cues from optic flow, vestibular signals, and proprioception caused by locomotion.
Portable media: human-made artefacts that are carried by the navigator and that can be passed on from person to person, such as a compass, stick charts, or tactile map.
Projection of imagined structures: imagining structures that go beyond the directly perceived features in the environment can aid navigation. Conceptual structures are superimposed through mental imagery into physical structures to facilitate cognitive processes. The classical case is imagining constellations out of arrays of stars.
Systematised knowledge: abstracted, theoretical bodies of knowledge in which constituent concepts bear structured relations to each other. An example is the hydrological system of the Evenki, in which tributaries connect to larger rivers. An important aspect of systematised knowledge is that it is shared in a community through enculturation, lore, and physical media.
Toponymic system: system of naming places, both particular places and types of place. Knowing the names of types of place helps recognising them and communicating about them. The name of the place goes hand in hand with associations for that type of place, such as the type of landscape surrounding the place, and the characteristic vegetation and fauna. Often, the placenames, and how they relate to each other, facilitate inferences that aid navigation (e.g., proximity to a river).

on observation and the consequent modelling of situations), and it has a dedicated language and methods of transmission [19]. All over the world, navigation depends on systematised knowledge. Navigators in the Pacific Ocean make extensive use of celestial schema [37], and Gwich'in people have an intricate system of inland stellar wayfinding [1]. The songlines of aboriginal cultures in Australia are oral representations of landscapes, and have both mythical and navigational value, because their mnemonic qualities serve to remember features that aid orientation [38].

One assumption in most cognitive science studies of navigation is that expert navigation corresponds to the use of allocentric representations [2]. However, this is not necessarily the case. Evenki knowledge of rivers takes the form of a diagram, and their toponymic system is not spatially arranged. Within anthropology, there was an active debate between mental map proponents [39],

Wayfinding: process or ability of reaching a destination in spatially extended environments.
Wind compass: in environments where the wind direction and characteristics (e.g., temperature, moisture, etc.) tend to be stable for certain periods (e.g., trade winds come from a particular direction), the wind becomes an important source of directional information. In some cultures, the combination of different periodically stable wind directions is systematised to form a 'wind compass', which is memorised.

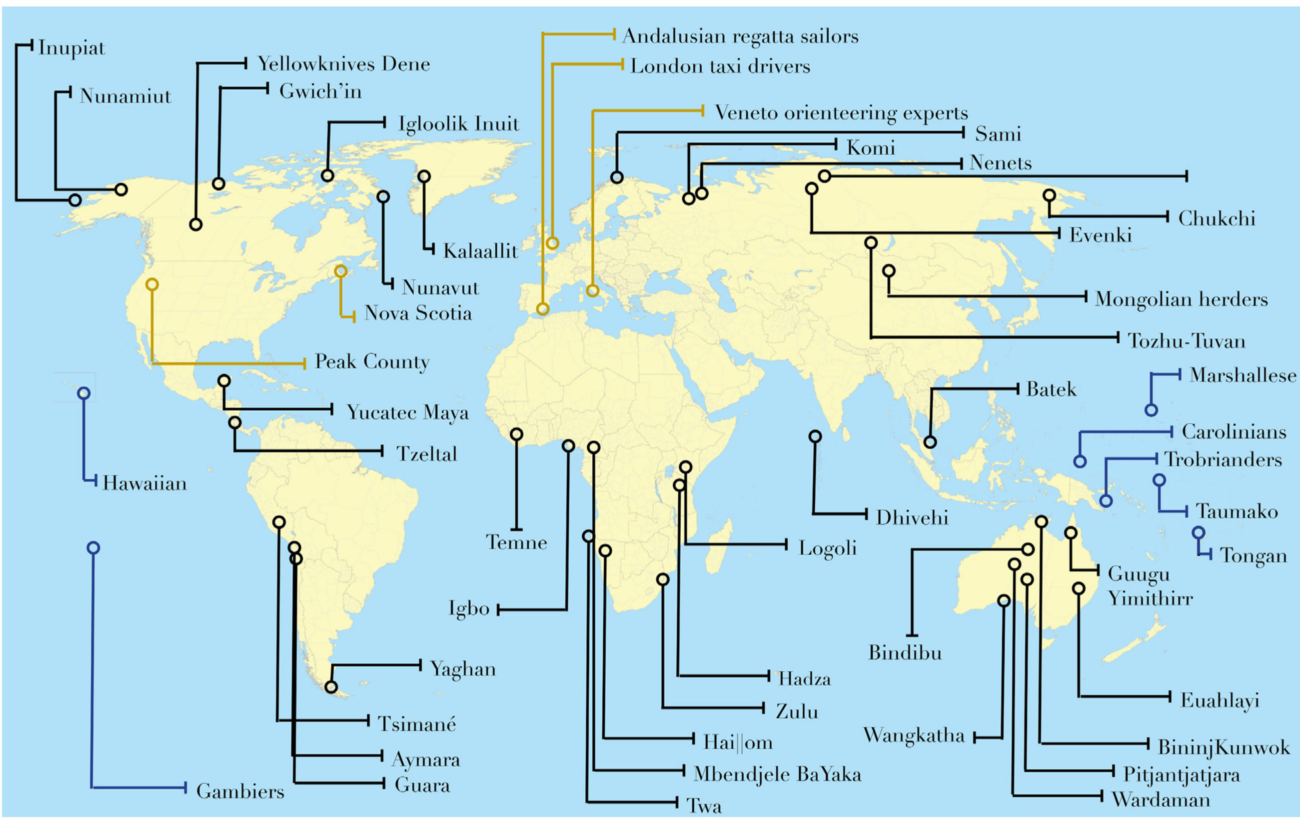

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Figure 1. World map indicating the locations of different cultures of traditional navigation. The map shows different populations for which there are corresponding publications documenting the traditional navigational culture of the population. The references for the work documenting the navigational culture of each population in the map, in alphabetical order, are as follows: Andalusian regatta sailors [89], Aymara [90], Batek [30], Bindibu [38], Bininj Kunwok [91], Carolinians [45], Chukchi [92], Dolgan [93], Euahlayi [38], Evenki [35], Guara [94], Guugu Yimithirr [18], Gwich'in [1], Hadza [88], Hai||om [95], Hawaiian [44], Igbo [96], Igloolik Inuit [46], Inupiat [97], Kalaallit [28], Komi [16], Logoli [98], London taxi drivers [41], Marshallese [87], Mbendjele BaYaka [69], Nenets [16], Nova Scotia deer hunters [27], Nunamiut [99], Nunavut [100], Peak Country search and rescue [101], Pitjantjatjara [32], Sami [102], Taumako [17], Temne [100], Tongan [103], Tozhu-Tuvan [104], Trobrianders [105], Tsimané [85], Twa [70], Tzeltal [26], Veneto orienteering experts [106], Wangkatha [38], Wardaman [107], Yaghan [108], Yellowknives Dene [1], Yucatec Maya [109], and Zulu [49]. The map is not exhaustive (e.g., we do not cover all the island cultures in Lewis's work [23]). Points on the map correspond to the location of the study, but some populations (e.g., Evenki) might dwell over much larger areas. The yellow connecting lines denote specialised subcultures of navigation within a broader western, industrialised population (e.g., London taxi drivers or Veneto orienteering experts). The blue connecting lines denote Pacific islander populations. By 'traditional navigation', we refer to methods used from cultures that do not use a westernised approach to navigation, such as using a cartographic map, magnetic/digital compass, or GPS. In many cases, this culture is under threat of disappearing; thus, documenting it and preserving the knowledge is important. Therefore, when we refer to existing navigational methods, they may be only used by a small group of people.

Table 1. Examples of traditional navigation techniques

Technique[a]	Example populations	Refs
Environmental cues		
Waves	Marshall Islands	[87]
Wind cues	Inuit (Greenland)	[28]
Slope	Tzeltal (Mexico); Nova Scotia hunters (Canada)	[26,27]
Ocean swell	Marshall Islands	[87]
Smoke signals	Igbo (Nigeria)	[96]
Stars	Yellowknives Dene (Canada); Gwich'in (USA)	[1]
Oceanic lights	Taumako (Solomon Islands)	[37]
Snowdrift	Inuit (Greenland)	[46]
Auditory cues	Batek (Malaysia)	[30]
Seaweed	Inuit (Greenland)	[46]
Olfactory cues	Hawaiian (USA); Pitjantjatjara (Australia)	[31,32]
Animal behaviour	Inuit (Greenland)	[46]
Systematised knowledge		
Maritime stellar wayfinding	Taumako (Solomon Islands)	[37]
Inland stellar wayfinding	Yellowknives Dene (Canada); Gwich'in (USA)	[1]
Toponyms	Evenki (Russia)	[19]
Landscape directionals	Inuit (Greenland)	[28]
Songlines	Aboriginal Australia	[38]
Hydrological knowledge	Evenki (Russia); Nenets, Komi (Russia)	[16,35]
The Knowledge of London	London taxi drivers (UK)	[41]
Gestures	Guugu Yimithirr (Australia); Hai//om (Namibia)	[18,95]
Visualisation techniques		
Bird's eye view	London taxi drivers (UK)	[41]
In-street view	London taxi drivers (UK)	[41]
Tiller 'inflating' the mainsail	Competitive western sailing	[43]
Hand-sky mapping	Hawaiian (USA)	[44]
Imaginary landmarks	Micronesian navigation	[23,45]
Projecting constellations	Gwich'in (USA)	[1]
Cognitive artefacts		
Tactile maps	Inuit (Greenland)	[48]
Sand maps	Wangkatha (Australia)	[38]
Stick Charts	Marshall Islands	[87]
Etchings	Bindibu (Australia)	[38]
Trail breaking	Inuit (Greenland); Yellowknives Dene (Canada)	[1,46]
Rock art	Zulu (South Africa)	[49]

[a]For traditional navigation, many techniques are combined into a holistic system (see e.g., [17]). The figure *Yahdii* in Gwich'in culture (see Figure 2 in the main text) is a constellation and, thus, systematised knowledge (e.g., about which attributes of *Yahdii* correspond to which landscape features at given times). In turn, this knowledge allows the traveller to use stars (environmental cues) to navigate by projecting the full constellation (through visual techniques).

who argued that wayfinding depended on stored spatial information, and practical mastery proponents, who argued that wayfinding depended on attunement to the environment [40]. Istomin and Dwyer [21] showed how the distinction corresponded to that between allocentric and egocentric

Box 1. Interplay of spatial cognition, language, and environment

A key distinction can be made between spatial representations in egocentric or allocentric frames of reference (FoR): when navigating, one can go left and then forward (egocentric), or north and then east (allocentric). In spatial language, FoR serve to encode projective space: the figure is anchored in relation to the ground, where these two entities could be not only locations, but also a particular orientation or a path (e.g., the trail starts north of the parking lot). Based on the egocentric–allocentric distinction, together with the concept of intrinsic spatial relations, Levinson [18] proposed three FoR for spatial language: intrinsic (anchored on an object based on its perceived asymmetry; e.g., in front of the TV, based on the orientation of that TV), relative (anchored on the viewpoint itself; e.g., in front of the TV, with 'front' being the side closest to the speaker), and absolute (anchored on fixed points of reference; e.g., north of the TV). In turn, geocentric has three subtypes [110]: absolute (vectors abstracted from the landscape; e.g., true north), geomorphic (vectors tied to landscape features; e.g., downriver), and landmark based (vectors relative to a topographic feature; e.g., mountainward).

When memorising a spatial array (e.g., of toys on a table), one can use an intrinsic, a relative, or a geocentric FoR. An interesting finding is that choice of FoR in spatial reasoning tasks tend to match the FoR that is dominant in the language spoken by the subject [18], although mismatches occur [110]. Some argue this is due to the influence of language on spatial cognition [111], while others claim that the environment is the ultimate cause of both linguistic and spatial cognition effects [112]. More recent evidence indicates that sociocultural factors have a role. In Dhivehi, women and younger speakers favour egocentric FoR compared with older and male speakers, who are more likely to have outdoor occupations [113]. The resulting picture is best captured by the sociotopographic model, which conceives spatial behaviour as determined by a complex interplay of environmental features, affordances, cultural practices, and linguistic factors [113–115]. Existing evidence for the sociotopographic view includes the diversity of environmental features invoked across Australian languages (e.g., coastlines, river drainage, or ruggedness) [114], the primacy of shape and function when conceptualising landscape [28,116], the influence of economic activity, literacy, and bilingualism [117,118], or the shift from geocentric FoR with the decline of nomadic pastoralism [119]. An interesting approach here is the combination of laboratory-based experiments and computational models to examine the evolution of spatial referencing systems [120].

frames of reference (environment centred/self centred) in psychology and argued that different cultures simply varied in the degree to which they relied on allocentric information. The Evenki are a case in point. Their ways of navigating are best explained as a series of local environmental adaptations that enable them to find their way in the taiga without relying on allocentric information.

Visualisation techniques and exploiting regularities

We have explored the cultural repertoire of expert traditional navigators in many natural environments. There are also experts who follow local navigational traditions within western culture and in urban environments, such as London licenced taxi drivers. London (UK) is an urban region of almost 26 000 streets. In the midst of this complexity, taxi drivers are able to quickly plan and execute routes all across the street network without requiring GPS. To do this, they go through many years of training. To acquire their 'Knowledge of London' and obtain their licence, taxi drivers need to be able to plan the shortest route between any two places, which they demonstrate in the exam for this licence by naming all the roads in that route in the correct order, including turning instructions [41]. In their training, they combine the use of static large maps with enacted navigation, driving around London to learn about the streets *in situ*. Analogously, when they plan routes, many taxi drivers combine two types of visualisation technique: they picture the map of London from a bird's eye view, charting subgoals along it, and they use their *in situ* experience to simulate in-street views of the route, which informs decisions about drop-off points [41,42] (Table 1).

Visualisation techniques are a common element of traditional navigation across many cultures. In western sailing traditions, there is a representational technique in which, when a sail is losing power and in danger of jibing, the sailor can point the tiller toward it and imagine it working as a hairdryer that 'inflates' the sail. The dynamic interplay of boat and wind is such that this visualisation trick ensures that wind restores power to the mainsail [43]. The regularities of the artefact–environment dyad (i.e., the boat at sea) allow for a computationally lean operation through the use of a projected causal chain from the tiller to the sail. Such techniques are inextricable from systematic knowledge: western sailors' vocabulary reflects their use of the wind as a frame of reference (e.g., 'luffing': turning the bow into the wind).

Exploiting regularities for visualisation is also present in the Pacific islands. There is an interesting technique coming from the revival of native cultures of navigation in Hawaii: the wayfinder holds up their hand, with the thumb against the horizon, and maps the height of celestial objects to physical features on their hand [44]. Another famous example is the 'etak' technique from the Carolinian Islands, in which the location of an island below the horizon is used to track progress against the movement of the stars [45]. The island appears in the navigator's imagination to move back along the horizon, such that the navigator creates a model of the voyage that they can manipulate from their point of view. Visualising constellations is another clear example, as shown in the figure of *Yahdii* in Gwich'in culture (Figure 2). We have seen how Inuit cultures use the wind as a cue, and imagination also has a role here. Primary winds that reliably blow in a particular direction exist as cardinal directions even when they are not blowing, and travellers can often visualise them as an animate object [46]. A haptic-auditory cue becomes a visual cue, and one that can be used when vision is generally impaired (e.g., in a snowstorm).

Some of these techniques involve explicit imagination, such as the simulated routes of London taxi drivers, and others involve a **projection of imagined structures** onto physical structures (e.g., seeing the stars as *Yahdii*). These are instances of enacting meaning, which is a culturally mediated act [47]. Even for the case of internal simulations of trajectories by taxi drivers, the imagined map of London only emerges thanks to the numerous hours of training using a real map (Figure 2C), and the imagined street-view route only emerges thanks to the many journeys taken by the taxi driver.

Cognitive artefacts and the internal–external divide

Cartographic maps, the magnetic compass, the sextant, and more recently, GPS all provide examples of tools used to aid navigation by many on our planet. Traditional navigation methods substantially expand this repertoire, from the Marshallese stick charts to the use of driftwood on the southeast coast of Greenland. There, the Inuit carved pieces of driftwood to represent the shape of the coast of particular regions [48]. When giving directions or telling stories about particular places, the driftwood maps were used as props, and the audience could retrace kayak journeys around the fjords by running their fingers along the curves in the driftwood. One advantage of these maps is that they can be sensed through touch when there is low visibility.

There are many cross-cultural examples of cognitive artefacts. The Wongai of the Eastern Goldfields in Australia create sand maps during narrations to support the audience's understanding of the landscape. The sand maps have a particular syntax (e.g., circles for important places) and they represent paths, water sources, and places of interest [38]. Sand drawings have the advantage of being dynamic, as one can easily redraw during narration. While the aforementioned examples are all in **portable media**, there are also stationary examples of navigational aids, such as Zulu rock art [49]. Rock provides a **durable media**, and the natural features of the rock can become part of the cartographic representation, with a smaller rock on top of a larger flat one representing homesteads on a hill.

This diversity of materials raises the question of what qualifies all these as cognitive artefacts. Moreover, there are many borderline cases that count as **naturefacts**, naturally occurring structures used for human purposes, such as the use of snowdrift to infer wind directions [50]. When we say that the aforementioned are all cognitive artefacts, we mean that they are designed to enhance the cognitive abilities of their users. They functionally contribute to performing a cognitive

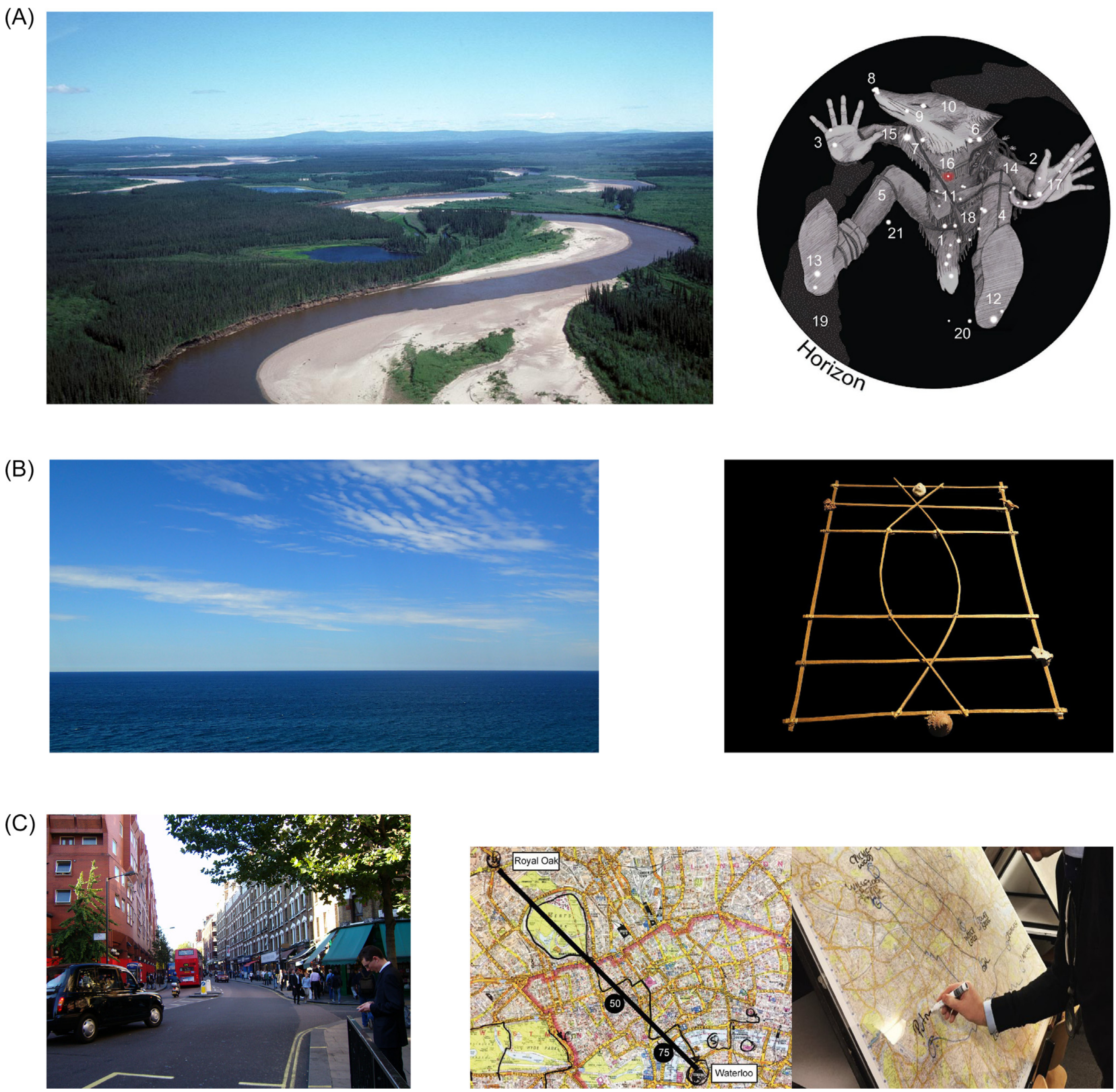

Figure 2. Different environments and navigational techniques created to navigate them. (A) Left, northern Alaska, territory navigated by the Gwich'in. Right: artistic depiction of the Gwich'in whole-sky constellation, the mythical creature *Yahdii* [1]. There is a mapping between the constellation and local landmarks of the Gwich'in territory at given times, such that *Yahdii* can serve as a celestial schema for inland orientation. The projection of occluded parts of this anthropomorphic figure allows travellers to infer the locations and spatial relationships of all its stars even when the constellation is partially obscured. (B) Left: view from the open ocean in the Pacific. Right: Marshallese stick chart representing major ocean swell patterns and the ways the islands disrupt those patterns [22]. (C) Aerial view of part of London's (UK) street network. Right: London taxi driver Knowledge School material in use by apprentice taxi drivers [41]. Maps are used to learn relations between places, to help with directional studies, and for planning the fastest routes. Photographs by US Fish and Wildlife Service (USFWS) (A), François Bianco (B, left), Rama (B, right), and Gerry Lynch (C, left).

task [50]. The function of the artefact is constrained by its materiality, but is not reduced to it. The driftwood map only represents the shoreline in the context of a meshwork of cultural practices. This echoes the emphasis in semiotic theory on understanding representational devices within the larger interrelated **information systems** of a culture [51]. We can clearly see this in the case of stick charts, teaching diagrams that only make sense within the larger practice of wave piloting [22]. Similarly, examples of star and of **wind compasses** are only usable within larger navigational systems [23,37].

Implications for the study of navigation in the cognitive sciences

We started our journey by exploring wave piloting in the Marshall Islands and, at each step of the way, we analysed a different aspect of navigational culture: environmental cues, systematic knowledge, visualisation techniques, and cognitive artifacts, as well as spatial language (Box 1). These aspects are, in fact, inseparable, because cultures of navigation are interrelated information systems. Sensing the waves can only work in the context of a rich body of knowledge about currents and swells, which in turn is passed on through the cognitive artifact known as stick charts. It is only thanks to this conceptual apparatus that waves are 'seen as' or 'felt as' indicators of remote islands. Training, lore, the syncing of body and environment, local techniques, and, above all, the landscape are all key elements that one needs to consider to understand real-world navigation. This is what it means for navigation to be situated, both culturally and environmentally, and it has momentous methodological consequences.

Anthropological evidence highlights the importance of key aspects of navigation that have been largely overlooked in cognitive science, such as visualisation techniques [52], navigation at sea [53], or the link between linguistic frames of reference and wayfinding [54]. It also invites cognitive scientists to immerse themselves in the community of study and to seriously consider how cultural factors influence spatial cognition. While this point has been made in some areas of psychology [55], it is not yet a widespread consideration in the study of human navigation. Most importantly, a deeper understanding of traditional cultures challenges several core assumptions in classical research in the cognitive sciences. Experimental work has largely studied clearly distinguishable visual landmarks [33], while real-world navigation involves multimodal evidence accumulation that flexibly adapts to environmental context. The literature we review also moves away from a narrow focus on internalised memory representations of spatial locations toward an understanding of navigation as a dynamic, action-oriented skill involving a heterogenous set of cognitive resources and heuristics (a recent neuroscience review by Ekstrom and Hill advocates for a move in a similar direction [56]).

Perhaps the most important challenge coming from anthropology concerns the association of expert navigation and the use of allocentric frames of reference [57–64]. The anthropological literature shows many examples of expert navigators who do not rely on the use of allocentric information, but rather on a combination of egocentric information, systematised knowledge, and locally adapted techniques. Relatedly, most experimental designs involve participants learning an environment through either direct exploration or cartographic representations that are both allocentric and Euclidean [10,41], while real-world learning often involves non-Euclidean representations, such as stick charts, and the transmission of spatial knowledge through lore, as is the case with the songlines of aboriginal cultures in Australia. Finally, the narrow focus on internalised memory representations in cognitive science means that we know relatively little about the role of cognitive artifacts in navigation. Even when psychology researchers approach the issue, they tend to study artifacts, such as GPS guidance, in which the majority of the navigational processes are offloaded wholesale onto an external resource [65]. By contrast, cognitive artifacts in traditional cultures transform rather than substitute navigational processes, Box 2. Direction pointing as a method to evaluate expert navigators

Pointing accuracy is a test for assessing navigation skill that is widely used both in anthropology and cognitive science. For example, Figure IA–C shows the accuracy of Hai//om people (Namibia), Guugu Yimithirr (Australia), and Dutch participants on a pointing task, respectively [18]. Rather than simply comparing raw performance scores across populations, the use of pointing tasks becomes more interesting by combining them with a multitude of factors. A recent study explored the three-way interaction between age, distance from camp to the test location, and sun visibility on errors in a pointing task designed to test the orientation abilities of the Mbendjele BaYaka people in the Republic of Congo [69]. They found that sun visibility increased pointing accuracy for young participants, particularly when they were far from the camp (Figure ID). However, the effect was less apparent in older participants, who exhibited high pointing accuracy even when the sun was not visible. At present, an interesting, underexplored angle is looking not only at pointing accuracy, but also at the biases underlying pointing errors; that is, trying to find what the elements are that affect participants' errors and how, which is often used in cognitive sciences as a way to model the underlying cognitive processes involved in a task [121]. Another promising avenue of research involving pointing tasks is incorporating new technologies. For instance, a study of seminomadic children in Northern Namibia combined pointing tasks with GPS tracking to assess mobility patterns to assess the effect of schooling on gender differences [70]. They found that schooling resulted in similar patterns of mobility for boys and girls, which reduced gender differences in navigational performance compared with adults in the same population. Recent advances in motion capture technology and image analysis can also be harnessed to construct better models of the bodily movement involved in pointing [122]. This is particularly relevant when we consider the gestural lexicon in cultures such as the Guugu Yimithirr, who point using large gestures that are correctly oriented by cardinal direction, and which are accompanied by a rich iconic system: the arm communicates very precise angles; the hand can point to a second location to form sequences of exact vectors; a flat hand can depict the steepness of a slope; the elevation of the arm can indicate distance to target; and a moving gesture can indicate a precise trajectory [18].

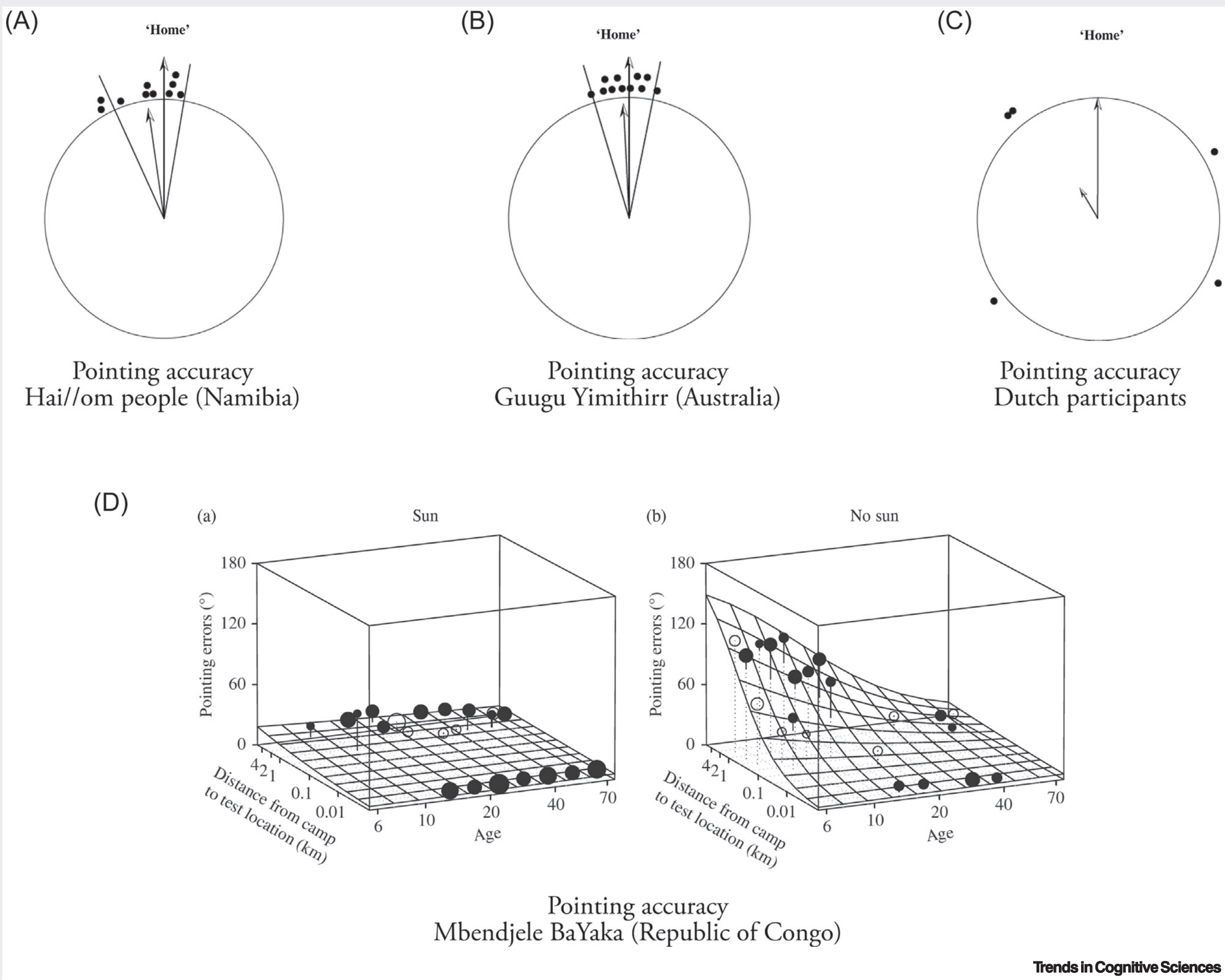

Figure I. Pointing accuracy across cultures.

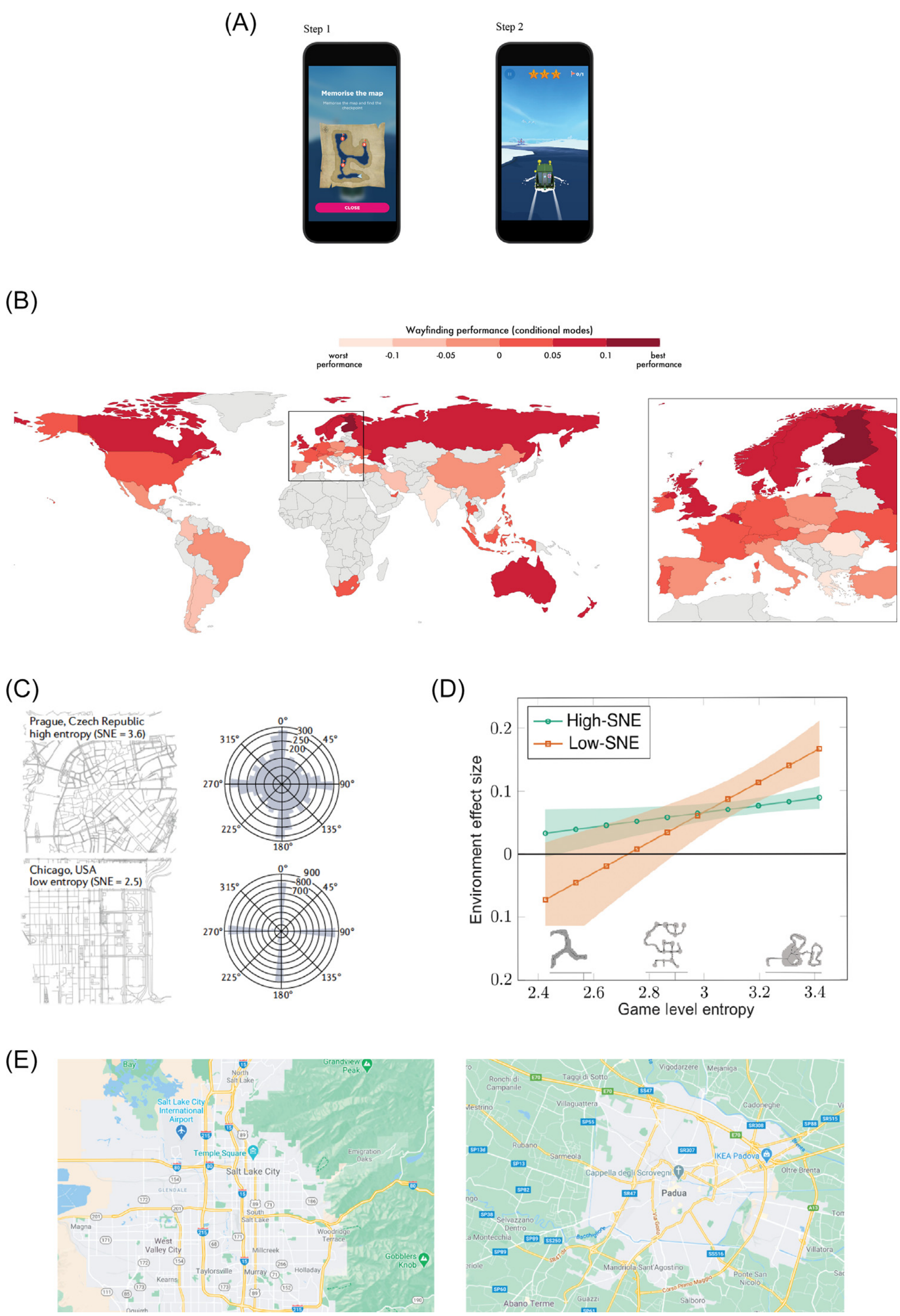

Figure 3. Exploration of cross-cultural navigation. (A) Interface of the standardised test of navigation, Sea Hero Quest (SHQ). SHQ has been shown to have good test–retest reliability [74] and to be predictive of real-world navigational ability: a study comparing participants' SHQ performance with performance in a real-world wayfinding task in London (and replicated in Paris) found a significant correlation between the two [10]. Analysis of the data showed that gender inequality across countries

(Figure legend continued at the bottom of the next page.)

which means that the individual user needs to be enculturated and able to skilfully recruit internal and external resources for navigation [66].

Methodological advances in the ecological study of navigation

The multifaceted character of navigational culture underscores the shortcomings of a narrow focus on a subset of the world population doing similar navigation tasks. Recent methodological developments in real-world approaches to cognition invite us to consider environmental control and ecological validity as orthogonal factors rather than as the two irreconcilable ends of a continuum [18,67,68]. Here, we explore how some of these developments can help with both the descriptive nature of much anthropological research [18] and the ecological validity of psychological research on navigation.

New technologies are already transforming the study of spatial cognition and can be harnessed to address the situated nature of navigation. GPS tracking and measures of pointing behaviour can help us study expert navigators across cultures [69–71] (Box 2). With the development of mobile touch-screen technology, it has been possible to provide remote VR tests of navigation and reach many populations, where the tests are gamified. Such gamified experiments, accessible through digital devices, facilitate both experimental control and the large-scale collection of cross-cultural data.

An example of how a mobile phone-based navigation testing can reveal insights into how culture and environment impact navigation has come from the Sea Hero Quest (SHQ) project [4,10,72–75]. In the mobile game SHQ, participants navigate a boat through different environments, which vary in their features (Figure 3). Since its launch, over four million people across 193 countries have played the game [4]. The participants contributed demographic information, and the wealth and detail of the data provided from the game have been used to look at the interaction of different demographic, cultural, and environmental factors. One key finding is that the environment that a person grows up in shapes navigation skill in later life [73]. Participants who grew up in the cities of countries that tend to be gird-like (i.e., low entropy in street orientations) were better at navigating grid-like environments, whereas those from rural or countries with no-grid-like cities were better at navigating environments with high entropy in street orientations (Figure 3). Big data approaches also offer a way of looking at the impact of cultural factors on navigational ability, such as Hofstede's cultural dimensions [75] or gender inequality [72].

Nevertheless, even such cross-cultural approaches leave out traditional cultures of navigation within a country. In fact, it is possible that the test itself is interpreted and performed differently

predicts gender differences in navigation ability [72], that 7 h of sleep is associated with a better navigation performance late in life across cultures [82], and that cultural norms around masculinity are associated with overestimation in navigation performance across countries [75]. (B) Wayfinding performance measured during virtual wayfinding tasks using SHQ. Countries filled with darker red colour performed better. Even in mass, cross-cultural data such as those provided by SHQ, there are notable gaps as indicated by the countries in grey. Moreover, there is an important risk of selection bias [73], and indigenous groups within each country are not represented. (C) Two examples of a city with a high (Prague) versus a low (Chicago) Street Network Entropy (SNE), a metric that is calculated from the Shannon entropy of the orientation distribution of the city based on the street network graph of each city. To the right of the plans for each city is the distribution of the street bearings for that city [73]. (D) Average SNE as a function of the environment effect size in each country. Positive values indicate an advantage of participants raised outside cities compared with their urban compatriots. Average SNE is the weighted average over the ten most populated cities of the country, weighted by their population. Squares and circles correspond to the low-SNE and high SNE country groups, determined with k-means [73]. (E) Environmental structure of Salt Lake City (USA) and Padua (Italy), two cities with very different configurations. In a recent experiment, participants from each city undertook different tests designed to assess their navigational performance and strategies. Their results showed that participants' navigational strategies were adapted to their local environment, and that participants in more complex environments (e.g., Padua) had better navigational abilities overall [83]. Adapted from [75] (B). Images from Google Maps (E).

in different traditional communities; for example, compare sea-going cultures, which make numerous assumptions about sailing versus a forest-dwelling culture whose participants have never seen the ocean. Nevertheless, screen-based methods offer a novel way of mass testing for navigation ability, and can be adapted to local cultures and environments (e.g., city-themed version of SHQ in [73]), as well as combined with other measures, such as pointing tasks, mobility tracking, and environmental analysis [70]. Moreover, testing methods such as SHQ can be used not only in participant crowdsourcing (i.e., one research team gathering data from large number of participants), but also in research crowdsourcing, in which a large number of researchers gather to work using a common framework and methodology, with each research team working with a different community [76]. Of course, gamified experiments are not sufficient in and of themselves to reflect the diversity of human wayfinding cultures, but they expand the experimental toolkit in novel directions, and hold great promise when combined with other, locally adapted approaches.

Beyond new ways to collect data, methods for analysis have also advanced. Machine learning approaches to the study of large-scale real-world data, such as the information generated from the tracking of mobile devices, provide a way to understand real-world navigation [77,78]. Bayesian procedures of complex system modelling are increasingly used for modelling real-world events [79], and there is a growing body of work on agent-based simulations of wayfinding [80,81]. The analysis of navigation behaviour goes hand in hand with the analysis of the environment in which that navigation takes place. Here, we highlight information-theoretic measures, such as the entropy of street networks [82,83], as well as metrics that have emerged from space syntax analysis in architecture [84].

Increasingly, anthropological work includes satellite imagery and GPS tracking technology to study navigation behaviour, such as the daily mobility of Tsimané forager-farmers in Bolivia [85]. Many recent anthropological studies of navigation already make use of computerised tests developed to work in the field [86]. Concerning spatial analysis, there are several environmental metrics that have started to be collected and used in anthropological work, including wave patterns for a study of Marshallese navigation [87], or the density of food energy in the landscape or the sinuosity of routes for a study of Hadza hunter-gatherers [88]. Overall, converging methodological developments across the cognitive sciences open the door for a truly interdisciplinary endeavour that does justice to the situated nature of navigation (see Outstanding questions).

Concluding remarks

From the atolls of the Pacific Ocean to the dense vegetation of the taiga and from the labyrinthine streets of London to the southeast coast of Greenland, we have found consistent evidence for how the diversity of landscapes in which humans dwell is mirrored in the diversity of navigational cultures. Current research on navigation within the cognitive sciences does not reflect this diversity. By looking at a multiplicity of anthropological studies, we tried to address this gap and offer an overview of the different ways in which humans adapt to their environment during navigation.

We have organised a structured way of thinking about the diversity of human cultures of navigation. We focused on four key aspects of navigational culture to guide our analysis: environmental cues, systematic knowledge, visualisation techniques, and cognitive artefacts. Environmental cues encompass features as widespread as wave patterns, slope, wind, oceanic lights, stars, or snowdrift [1,17,22,26,28,46]. Experiencing these features as cues involves multiple sensory modalities and depends on both embodied sensing and enculturation [30,32]. As for systematised knowledge, we have seen how different bodies of knowledge are intertwined. The Evenki knowledge of rivers is connected to their knowledge of landscape types [19]. These knowledge systems are also embedded in material media, as is the case of Marshallese stick

Outstanding questions

How can researchers actively engage indigenous collaborators in the study of navigational cultures? It is paramount to avoid 'helicopter science' and to consider local nonwestern, noncolonial, knowledge systems. Existing efforts to integrate traditional ecological knowledge in areas such as health, sustainability, and conservation can show us the way forward in cognitive science.

How can navigation studies account both for cross-cultural and intra-cultural variation? Environment and culture are fundamental, but they intertwine with individual factors. A first step is collecting more individual socio-demographic data and triangulate them with ethnographic data about the subject's navigational culture.

Can studies on navigation provide useful clues for the development of culturally appropriate and accessible navigation technologies for diverse populations? This is particularly pressing because widespread technologies, such as GPS guidance, can hinder the development and transmission of navigation skill in traditional cultures. A deeper understanding of local traditions of navigation, together with knowledge co-production in the development of technologies, can help revert this trend.

How can we address the challenges in performing cognitive testing in nonliterate populations? Cognitive tests are usually boring, abstract tasks that are challenging for people not exposed to formal education. A good starting point are advances in dementia screening, an area where researchers have had to develop spatial ability tests for a nonliterate population. As for technological barriers, researchers can use more intuitive interfaces, such as VR, voice commands, and tactile screens.

How can we fill in the gaps in the data of mass cross-cultural samples? While large, cross-cultural samples are a promising avenue of research, there is an important risk of selection bias, and indigenous cultures are often underrepresented even in such cross-cultural studies (see Figure 3 in the main text). A possible way to do this is to combine cross-cultural big charts [22]. Importantly, some cultures rely more than others on spatial information in an egocentric frame of reference, and there are many ways in which people solve local environmental challenges without relying chiefly on map-like mental representations [21]. We have also shown that visualisation techniques can involve offline mental imagery (e.g., imagining a route across London [81]) or the projection of imagined structures onto physical structures (e.g., seeing a set of stars as a constellation [1]). These techniques are a culturally mediated act, and often exploit agent–environment regularities [43], as when Hawaiian wayfinders map the height of celestial objects to physical features on their hand [44]. Finally, we have seen how a wide-ranging collection of artefacts that spans both portable and durable media [48,49] can enhance the cognitive abilities of their users to aid navigation. All of these elements work together as a mutually entrenched system that is adapted to the particular environment in which navigation takes place. New research methods provide exciting avenues for the study of navigation, integrating the approaches to traditional navigation with those of the laboratory [4,67]. Not only can future research help us understand human behaviour more deeply, but it can also help us preserve and understand the rich cultures on our planet that are under threat of disappearing.

data with data arising from a large international group of researchers, each collaborating with a local population, but under a single unifying framework.

What is the impact of cultural change on navigation? Cultures are not static. Within many indigenous cultures, occupations are changing, and traditional skills declining. This issue highlights the importance of intergenerational studies that account for factors such as schooling and technology use.

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Declaration of interests

None declared by authors.

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