Received: 14 July 2021 | Revised: 14 October 2021 | Accepted: 5 November 2021

DOI: 10.1002/hipo.23395

COMMENTARY

WILEY

London taxi drivers: A review of neurocognitive studies and an exploration of how they build their cognitive map of London

Eva-Maria Griesbauer[1] | Ed Manley[2,3,4] | Jan M. Wiener[5] | Hugo J. Spiers[1]

[1]Department of Experimental Psychology, Division of Psychology and Language Sciences, Institute of Behavioural Neuroscience, University College London, London, UK

[2]Centre for Advanced Spatial Analysis, University College London, London, UK

[3]The Alan Turing Institute, London, UK

[4]School of Geography, University of Leeds, Leeds, UK

[5]Department of Psychology, Ageing and Dementia Research Centre, Bournemouth University, Poole, UK

Correspondence
Hugo J. Spiers, Department of Experimental Psychology, Division of Psychology and Language Sciences, Institute of Behavioural Neuroscience, University College London, London, UK.
Email: h.spiers@ucl.ac.uk

Funding information
Engineering and Physical Sciences Research Council; Ordnance Survey

Abstract

Licensed London taxi drivers have been found to show changes in the gray matter density of their hippocampus over the course of training and decades of navigation in London (UK). This has been linked to their learning and using of the "*Knowledge of London*," the names and layout of over 26,000 streets and thousands of points of interest in London. Here we review past behavioral and neuroimaging studies of London taxi drivers, covering the structural differences in hippocampal gray matter density and brain dynamics associated with navigating London. We examine the process by which they learn the layout of London, detailing the key learning steps: systematic study of maps, travel on selected overlapping routes, the mental visualization of places and the optimal use of subgoals. Our analysis provides the first map of the street network covered by the routes used to learn the network, allowing insight into where there are gaps in this network. The methods described could be widely applied to aid spatial learning in the general population and may provide insights for artificial intelligence systems to efficiently learn new environments.

KEYWORDS

cognitive maps, learning strategies, navigation, spatial cognition, spatial learning, wayfinding

1 | INTRODUCTION

The ability to navigate an environment depends on the knowledge of that environment. This knowledge can be gained in multiple ways, such as via instructions on GPS devices, memorizing a cartographic map, or through exploration. The knowledge formed can vary from very imprecise to extremely accurate, depending on the complexity of the environment, the level of exposure to the environment and individual differences (Ekstrom et al., 2018; Schinazi et al., 2013; Weisberg et al., 2014; Weisberg & Newcombe, 2016). Over the last decades, there has been increasing interest in understanding how different methods for learning impact the acquisition of spatial knowledge (e.g., Balaguer et al., 2016; Dahmani & Bohbot, 2020; Gardony et al., 2013; Hejtmánek et al., 2018; Ishikawa et al., 2008; Münzer et al., 2006, 2012; Siegel & White, 1975; Streeter & Vitello, 1986) and how individuals differ in their capacity to learn to navigate new environments (Burles & Iaria, 2020; Coutrot et al., 2018, 2019, 2020; Feld et al., 2021; Newcombe, 2018; Weisberg & Newcombe, 2016).

Despite GPS devices being a preferred method of navigation for many (McKinlay, 2016), the increased use of GPS devices appears to have a negative impact on spatial memory (Dahmani & Bohbot, 2020; Ruginski et al., 2019) and is associated with habitual learning of a particular route (Münzer et al., 2006). In contrast to GPS-based instruction-guided navigation, "map-based navigation" (relying on memory for the map) has been found to support spatial learning, knowledge acquisition of the environment and improved flexible navigation performance (e.g., Ishikawa et al., 2008; Münzer et al., 2006, 2012). Such flexible navigation relying on long-term memory is associated with the construction of a cognitive map, which stores the allocentric information about the structure of the environment enabling shortcuts and efficient detours around unexpected obstacles (O'Keefe & Nadel, 1978; Tolman, 1948).

A range of evidence indicates that within the brain the hippocampus provides a cognitive map of the environment to support memory and navigation (Epstein et al., 2017; Gahnstrom & Spiers, 2020; O'Keefe & Nadel, 1978) and damage to the hippocampus disrupts navigation (Morris et al., 1982; Spiers, Burgess, Hartley, et al., 2001). Hippocampal neurons encode spatial information (O'Keefe & Nadel, 1978) and for a selected group of individuals, who spend their daily lives navigating using map-based recall of space, their posterior hippocampal gray matter volume increases with years of experience and is larger than in the general population (Maguire et al., 2000). These individuals are licensed London taxi drivers. Here, we review the past literature from studies of London taxi drivers and explore how they learn the large amount of knowledge required to navigate London, which evidence suggests drives the changes in their hippocampus (Woollett & Maguire, 2011).

2 | A REVIEW OF RESEARCH ON LONDON TAXI DRIVERS

Licensed London taxi drivers are unusual among taxi drivers. They are able to mentally plan routes across an environment that contains more than 26,000 streets within the six-mile area around Charing Cross, the geographic center of London (A to Z from Collins The Knowledge, 2020). They are required to have sufficient knowledge to also navigate main artery roads in the suburbs—known as "The Knowledge." This area covers almost 60,000 roads within the circular M25 (The London Taxi Experience—The Knowledge, 2020; numbers may vary depending on sources, road types and the definition of the boundary of London). What makes licensed London taxi drivers unique is that they have to accomplish this using their own memory, without relying on physical maps or navigation aids. They are also the only taxi drivers permitted to pick up customers when hailed in the street, due to their license to operate. In the rest of this article, we refer to them as London taxi drivers, but readers should note that our analysis pertains only to licensed taxi drivers, who are also referred to as "London cabbies."

Changes in the hippocampal gray matter density in London taxi drivers were first reported by Maguire et al. (2000) using a cross-sectional study of London taxi drivers and magnetic resonance imaging (MRI) measures, including voxel-based morphometry (VBM). Maguire et al. (2000) speculated that because rodent and avian species can show variation in the size of their hippocampus with the demand on spatial memory (Lee et al., 1998; Smulders et al., 1995), it might be possible that London taxi drivers would show similar differences due to their profession. There were two main findings from this study: (i) compared to age and gender matched control participants, London taxi drivers had an increased gray matter density in their posterior hippocampus and a decreased gray matter density in their anterior hippocampus, (ii) years of experience was positively correlated with gray matter density in the right posterior hippocampus and negatively correlated with anterior cross sectional volume. Thus, there is no evidence for a globally larger hippocampus, but rather more experienced taxi drivers show a significant difference in the amount of gray matter along the long-axis of the hippocampus.

Following the discovery of differences in hippocampal size in London taxi drivers by Maguire et al. (2000) numerous studies have explored their brain function and cognition. MRI has provided further evidence of structural differences in their hippocampus, with three further studies supporting the initial findings (Maguire, Woollett, & Spiers, 2006; Woollett et al., 2009; Woollett & Maguire, 2011). To provide a more precisely matched control group to London taxi drivers, MRI structural measures were contrasted between London taxi drivers and London bus drivers. If the gray matter changes in taxi drivers are driven by daily driving and/or daily exposure to London, then bus drivers should have a similar hippocampal size to taxi drivers as they daily drive routes through London. However, if it is using extensive spatial knowledge that underlies the differences in gray matter density then London taxi drivers and bus drivers should differ. Results revealed that compared to London bus drivers, London taxi drivers have increased posterior hippocampus gray matter density, decreased anterior hippocampal gray matter density (Maguire, Woollett, & Spiers, 2006), replicating previous results (Maguire et al., 2000). While bus drivers show no relationship between hippocampal volume and years of experience, London taxi drivers were again found to show a positive correlation between posterior hippocampal gray matter volume and years of experience (Maguire, Woollett, & Spiers, 2006).

While cross-sectional studies of gray matter density provide evidence that changes in hippocampal volume may occur with exposure over time, they do not track individuals over time to provide a more reliable measure of structural changes with experience. Examining brain changes longitudinally within subjects, Woollett and Maguire (2011) found that an increase in the posterior hippocampus gray matter density after the years spent learning the Knowledge and passing the exam required to become a licensed taxi driver (Woollett & Maguire, 2011). Notably, taxi drivers showed no differences in hippocampal volume prior to starting training to non-taxi drivers, indicating that taxi drivers may not be predisposed to having a larger hippocampus as part of what predisposes someone to choose to train as a taxi driver. Intriguingly, those who failed to qualify did not show a change in their hippocampal size, indicating that it is not sufficient to spend time training, training must be applied effectively for changes in posterior gray matter density to become evident. Furthermore, cross-sectional evidence from measuring hippocampal size in medical professionals revealed no correlation between years of experience and hippocampal structural measures (Woollett et al., 2008). This suggests that it is unlikely to be storing the memory of all the street names that underlies the correlation between hippocampal volume and years of experience operating a London taxi.

Following the discovery of gray matter differences in London taxi drivers a number of studies have explored the extent to which hippocampal size might predict navigation ability. The first study to explore this in a sample of 23 participants found no association between posterior gray matter volume and navigation ability on a virtual navigation task (Maguire et al., 2003). However, a number of subsequent studies have reported a relationship between measures of hippocampal structure and navigation performance (Bohbot et al., 2007; Brunec et al., 2019; Chrastil et al., 2017; He & Brown, 2020; Hodgetts et al., 2020; Konishi & Bohbot, 2013; Schinazi et al., 2013; Sherrill et al., 2018; see also Hao et al., 2017). More recently, two studies with larger samples have found no relationship between hippocampal structure and either navigation (Weisberg et al., 2019) or route sequencing (Clark et al., 2020). Thus it remains a matter of debate whether in non-taxi drivers there is a link between hippocampal structure and navigation performance (see Weisberg & Ekstrom, 2021 for review).

Acquiring the Knowledge of London seems to come at a cost of learning and retaining new visuo-spatial information, which co-occurs with a concurrent volume decrease in the anterior hippocampus (Maguire, Woollett, & Spiers, 2006; Woollett & Maguire, 2009, 2012). However, in the small sample studied by Maguire, Woollett, and Spiers (2006) no significant correlation was present between anterior gray matter density reduction and the performance on visuospatial tasks. Functional neuroimaging studies have shown engagement of their posterior hippocampus when verbally recalling routes (Maguire et al., 1997) and at the start of the route when navigating a highly detailed virtual simulation of London (Spiers & Maguire, 2006a, 2007a). Other research with London taxi drivers has revealed insight into spontaneous mentalizing (Spiers & Maguire, 2006b), remote spatial memory (Maguire, Nannery & Spiers, 2006), emotions during navigation (Spiers & Maguire, 2008), the neural basis of driving a vehicle (Spiers & Maguire, 2007b), the features of street network that define a boundaries for navigation (Griesbauer et al., 2021) and the route planning process (Spiers & Maguire, 2008). London taxi drivers have also been shown to be better than non-taxi drivers at learning new routes (Woollett & Maguire, 2009).

Despite the numerous studies exploring London taxi drivers, little attention has been paid to how London taxi drivers learn and memorize the layout and landmarks in London (Skok, 1999). Many questions arise when considering this. How is their exploration structured? What do they study when examining maps? How are map and physical travel experience integrated? What role does mental imagery play in aiding their learning? How do they exploit the hierarchical structure of London's layout? Are major roads mastered before minor roads? In this observational report we provide the first investigation of London taxi driver's learning process and the methods and techniques that enable them to retain and use such a large amount of real-world spatial information for efficient navigation.

3 | METHODS TO STUDY LEARNING OF THE KNOWLEDGE

To understand the learning process of taxi drivers, different types of sources of information have been consulted. These sources included (a) a semi-structured interview (ethics approval was obtained under the ethics number CPB/2013/150) with a teacher from a London *Knowledge school* (here referred to as K.T. for "*Knowledge Teacher*"), (b) an email exchange with Robert Lordan, the author of "The Knowledge: Train Your Brain Like A London Cabbie" (Lordan, 2018), (c) an open introductory class of the *Knowledge of London* and regular scheduled classes for current students, (d) school specific study material, and (e) online information from the TfL (Learn the Knowledge of London, Transport for London, n.d.; Electronic blue book, 2019).

The interview with the teacher from the *Knowledge school* was audio-recorded and transcribed. The transcription of the interview can be found in Appendix S1. The teacher gave written consent for the content of this interview to be cited and published. Additionally, attendances of *Knowledge school* training classes, including an introductory class and several classes with more advanced students, allowed us to observe and understand the training process in more detail.

The information collected from these sources was systematically reviewed to report on (a) the ways spatial information is structured and presented for the learning process, (b) the techniques and methods used to learn this spatial information, and (c) how this knowledge is tested and the later perception of this knowledge as a taxi driver. A summary for each of these categories was created, starting with verbal reports (interview [Appendix S1], *Knowledge school* classes). This information was cross-referenced with and extended by unreported information from other, published, or official sources (e.g., study material, online booklets by TfL).

4 | OBSERVATIONS

Taxi drivers in London have to demonstrate a thorough Knowledge of London within the six-mile radius originating at Charing Cross (see Figure 1a) to earn the green badge that qualifies them to drive a "black cab" taxi (Electronic blue book, 2019). Within this area, taxi drivers are expected to plan a route (i.e., the "runs") based on the shortest distance between any two potential places of interest (i.e., the "points") their customers might travel from or to, such as restaurants, theaters, hospitals, sports centers, schools or parks (cf. Electronic blue book, 2019, for a complete list). Taxi drivers are also expected to name all roads or streets that are part of that run in the correct, sequential order, including traveling instructions, such as turns (Electronic blue book, 2019).

Historically, the exact roots of the *Knowledge of London* are unclear as written evidence is mostly missing. The first licenses and regulations for horse-driven carriages date back to the early 1600s by Oliver Cromwell (June 1654: An Ordinance for the Regulation of Hackney-Coachmen in London and the places adjacent, 1911; London Metropolitan Archives, 2013; Lordan, 2018; Newton, 1857). However, in 1851 the Great Exhibition in Hyde Park revealed incompetent navigation skills of the carriage drivers of those days. These initiated a series of complaints and forced authorities in the following years to set up stricter qualification requirements for drivers to test their knowledge of important streets, squares and public buildings (A to Z from Collins—The Knowledge, 2020; Lordan, 2018; Rosen, 2014). This scheme was officially introduced in 1865 (Learn the Knowledge of London, Transport for London, n.d.). The requirements in relation to the content of the *Knowledge* have since hardly changed and remained in place (The Knowledge, 2020) despite the technological innovations that have produced navigation aids, such as GPS devices, that

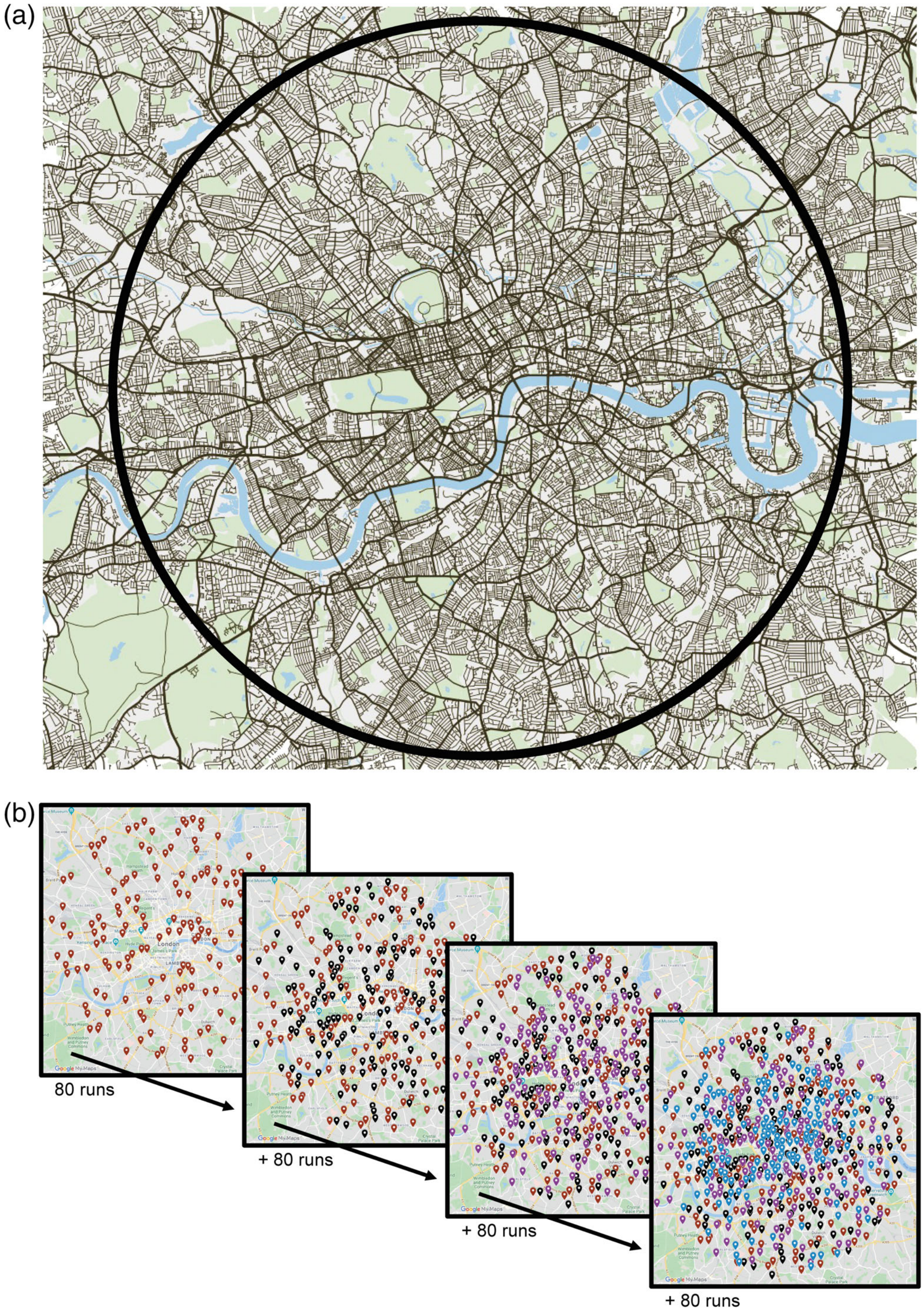

FIGURE 1 The Knowledge of London and the Blue Book. (a) London taxi driver students are expected to learn the street network and all potential points of interest within the six-mile radius around Charing Cross (black circle), which is called the "*Knowledge of London*." (b) To support the learning process of this area, the Blue Book was created. It contains 320 origin–destination pairs and the shortest route (i.e., "*run*") connecting those pairs. When mapped chronologically in groups of 80 *runs*, the network of origin–destination pairs starts overlapping and becomes denser. Red: The first layer of the first 80 origin–destination pairs. Black: The second layer of the origin–destination pairs for *runs* 81–160. Purple: The third layer of origin–destination pairs for *runs* 161–240. Blue: The final layer of the last 80 origin–destination pairs for *runs* 241–320. *Map sources*: (a) Mapbox (2020) and (b) My Maps by Google Maps

facilitate and guide navigation. The following sections will outline how this is achieved by taxi drivers.

4.1 | Presentation of spatial information in *Knowledge* schools

To help students to acquire the fundamentals of the *Knowledge of London*, the Blue Book (the origin of this name is unclear) was designed, which, in its current form, was put into place in 2000 (interview with K.T., Appendix S1). It contains 320 origin–destination pairs, their corresponding *runs*, as well as additional *points* related to tourism, leisure, sports, housing, health, education, and administration (Electronic blue book, 2019). In total, there are about 26,000 different streets and roads (Eleanor Cross Knowledge School, 2017) and more than 5000 *points* (Full set of Blue Book Runs, 2020) listed in the *Knowledge* schools' versions of the Blue Book. However, this knowledge is incomplete. By the time students qualify, they will have extended their knowledge to identify more than 100,000 *points* (The London Taxi Experience—The

Knowledge, 2020) in a street network of about 53,000 streets (OS MasterMap Integrated Transport Network, 2018). This covers not only the six-mile area, but extends to all London boroughs, including major routes in the suburbs.

The 320 origin–destination pairs of the Blue Book with their corresponding *runs* are structured into 20 lists of 16 pairs each, which are designed to systematically cover the six-mile radius: In a chronological order, as listed in the Blue Book, the majority of origin–destination pairs have an origin in the same postal districts as the destination of the previous origin–destination pair and spread across London throughout each list (Electronic blue book, 2019). When mapped in layers of four, the first 80 *runs* (i.e., five lists) provide an initial rough coverage of London. This coverage becomes denser with each of the remaining three layers that are shifted slightly against each other to fill in the gaps (Figure 1b).

Each of the origins and destinations in the Blue Book also require students to learn the nearby environment within the quarter mile range. That area around a Blue Book *point* is called the "*quarter mile radius*," or in short: the "*quarter-miles*" and is considered as ideal for learning small areas of the environment without overloading students with information (interview with K.T., Appendix S1; Learn the Knowledge of London, Transport for London, n.d.; Electronic blue book, 2019). For the first and most famous *run*, which connects Manor House Station to Gibson Square, the quarter-mile radius is illustrated in Figure 2a. It contains about 8 additional *points*, numbered 1–8. These are chosen by each *Knowledge school* individually and can differ between schools. The additional *points* serve as initial motivation for students to explore the quarter-miles and learn which streets link these points to each other. Knowledge of the remaining, unmentioned *points* in the area will be obtained by each student gradually as they progress through the *Knowledge of London* by studying maps and exploring the quarter-miles in person.

Mapping the origin–destination pairs with their corresponding quarter-miles, highlights how the areas locally link to each other (Figure 2b). To create such an overlap that sufficiently covers the whole six-mile area around Charing Cross (also see Figure 2a), 640 *points* are required, thus explaining the total number of 320 Blue Book *runs*. Since each *point* is closely surrounded by nearby origins and destinations of other *runs*, information is provided about how an area can be approached from or left in different directions. For Manor

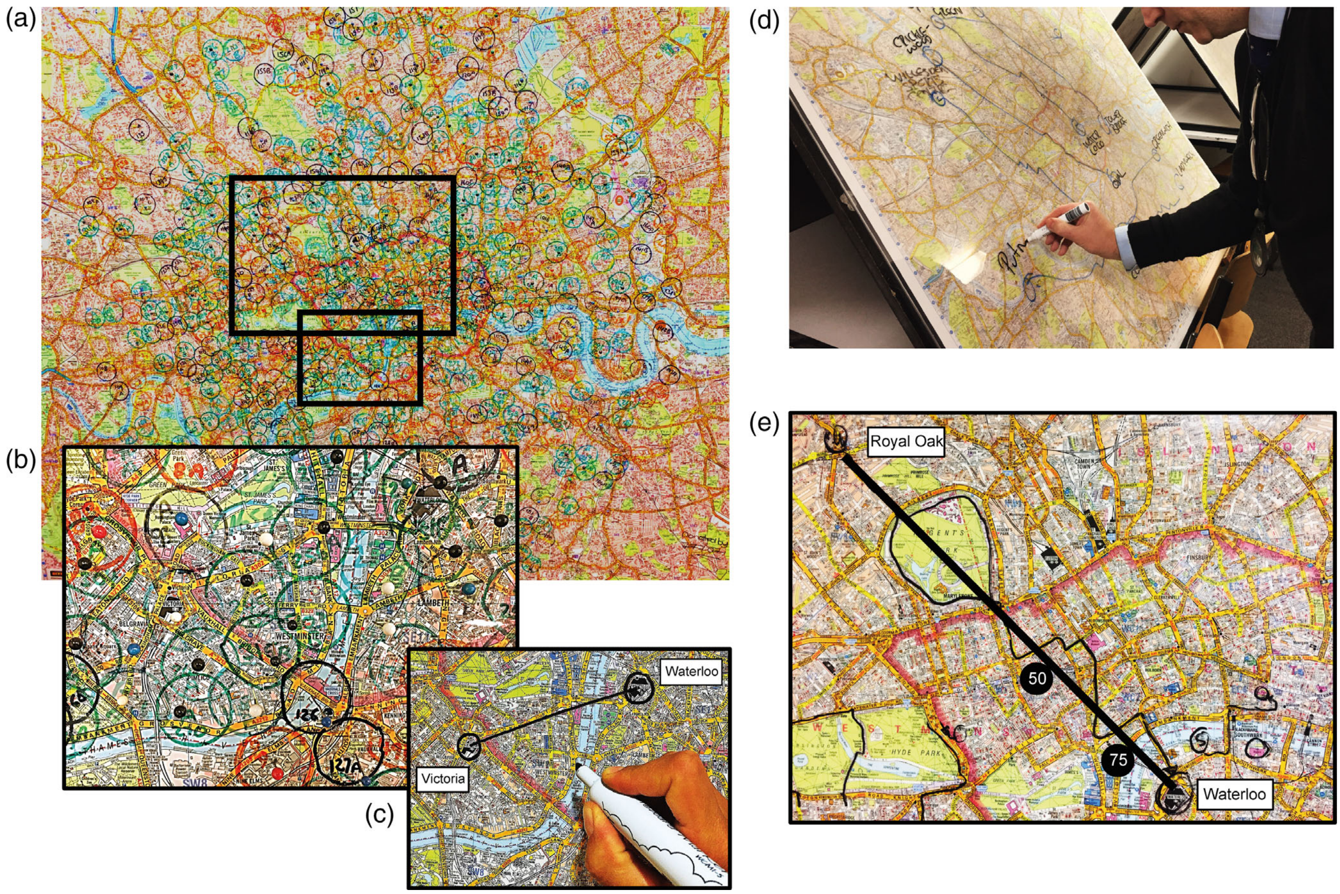

FIGURE 2 Example of Knowledge school material in use. In *Knowledge schools*, wallpaper maps (a) are used to illustrate the coverage of London within the six-mile area by the quarter mile radii (b). These maps support the learning of relations between two places and clear up misconceptions such as Victoria being located further north than Waterloo, which is owed to a change in direction of the River Thames (c). "The cottoning up of two points," a piece of string that is used to create a direct line between the points, is a common method to help with directional studies (c) and planning the most direct routes (d, e). Additionally, students use 50% and 75% markers along the direct line (e) to create subgoals that help to plan the *runs Source*: Knowledge Point School, Brewery Road, London, UK

House (Figure 2b) these *points* have been indicated by blue and red quarter-miles for nearby origins and destinations, respectively, in Figure 2b. To visualize this information across the entire six-mile area of London and keep track of their progress while learning the Blue Book, trainee taxi drivers mark the origins and destinations, including the quarter-miles, in a large, all London map (Figure 2a,b; *Source*: Knowledge Point Central, Brewery Road, London, UK).

Studying maps by visualizing the topological relationship between areas also helps to avoid misconceptions about the city's geography that could lead to mistakes in route planning. For instance, deviations from the more generally perceived west–east alignment of the river Thames can cause distortions (cf. Stevens & Coupe, 1978). Often Victoria station, located north of the river, is incorrectly perceived further north than Waterloo Station, which is on the southern side of the river, but further east then Victoria (see Figure 2c). This misconception is due to a bend of the river Thames, that causes the river to flow north (instead of east) between Victoria and Waterloo.

In the Blue Book, the 320 *runs* connect the origin–destination pairs through the route along the shortest distance for each pair (Electronic blue book, 2019). These pairs were chosen to create *runs* that are about two to three miles long and mainly follow trunk or primary roads. Here, trunk roads are the most important roads in London after motorways, providing an important link to major cities and other places of importance, with segregated lanes in opposite directions (Key:highway, 2020). Primary roads are defined as the most important roads in London after trunk roads, usually with two lanes and no separation between directions, linking larger towns or areas (Key: highway, 2020). Since these are often printed in orange and yellow in paper maps, taxi drivers also refer to them as "*Oranges and Lemons*" (interview with K.T., Appendix S1). Trainee taxi drivers visualize these *runs* on all London maps to learn and practice recalling them (Figure 2d, credit: Knowledge Point Central, Brewery Road, London, UK). *Knowledge schools* provide the 320 *runs* for the *points* of the Blue Book but encourage students to plan these *runs* before checking the up-to-date solution. To plan a *run* using the shortest distance and avoid major deviations (as required for the examinations), drawing the direct line (i.e., "*as the crow would fly*") or spanning a piece of cotton between the *points* is essential (Figure 2e). This so-called "*cottoning up*" also helps students to learn relations between places (Figure 2c) and visualize the map to find ways around obstacles, such as Regent's Parks, or to select bridges for crossing the river (Figure 2e) during the "*call out*" of the *run* (i.e., the recall of the street names in order along shortest route without using a map). Additionally, it provides opportunities to set subgoals, the "*50% and 75% markers*." These markers are set where the line coincides with major roads or bridges, about halfway or three quarters along the line. These distances are guidelines

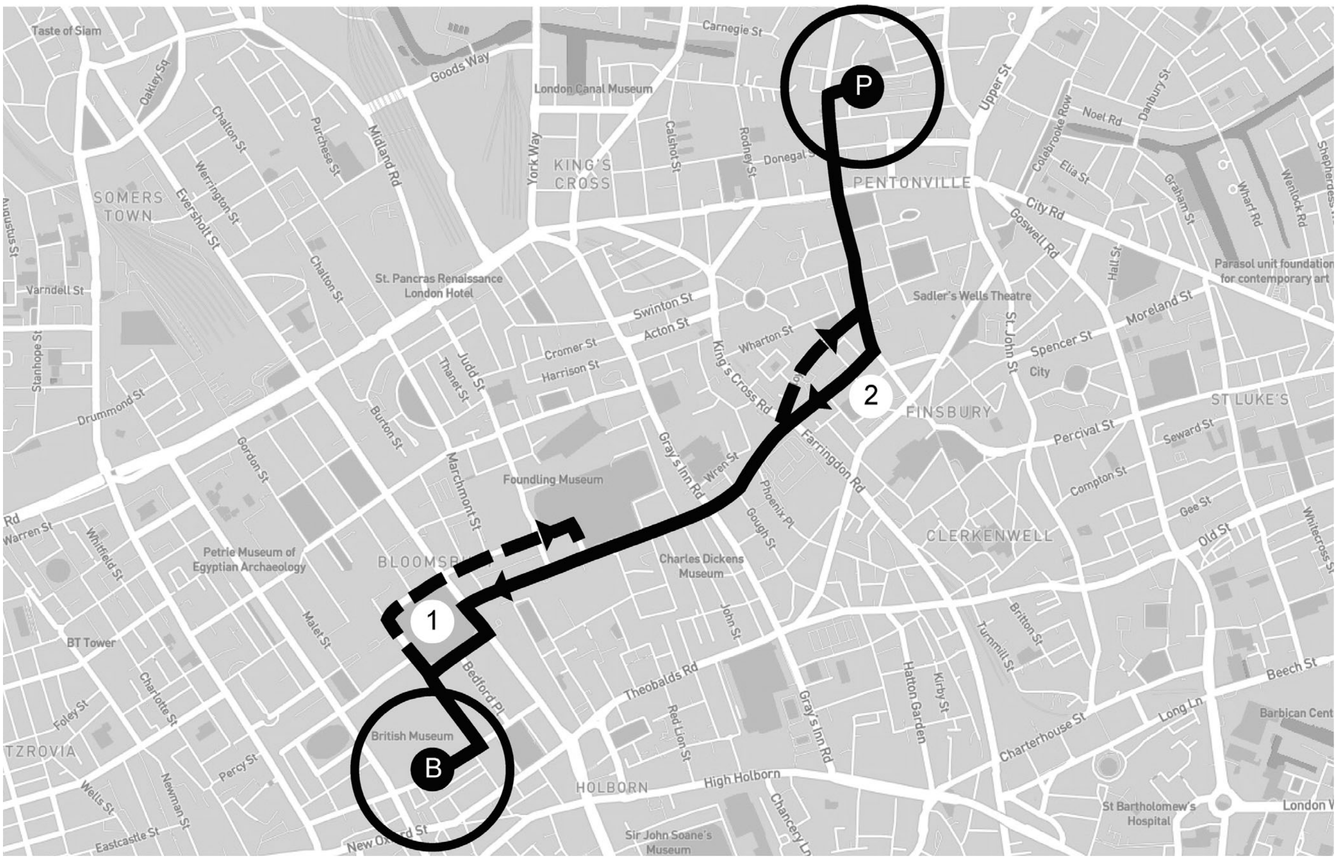

FIGURE 3 Runs and reverses runs. Due to one-way systems or turning restrictions, some *runs* differ when planned in reverse (dashed line), not allowing to simply invert the original sequence of streets taken (black line). This is the case for the *run* from Islington Police station (P) to the British Museum (B). When reversed, the one-way systems at Russell Square (1) and at Margery Street (2) require adaptation to traffic rules, resulting in differences between the *runs* and its reverse *run*. Figure is based on learning material from Taxi Trade Promotions

only, and sometimes bullets are set at other distances for streets and places along the direct line that facilitate planning in stages. These markers help students to stay close to the direct line, while breaking down longer *runs* in smaller sections and reduce the number of steps they have to plan for at a time (Figure 2e). Due to one-way streets and turning restrictions, *reverse runs* from the initial destination to the initial origin can differ. Therefore, the streets and roads cannot simply be called in reverse order but have to be learned separately (Figure 3).

The *runs* of the Blue Book form a network of routes that covers the six-mile area centered around Charing Cross (Figure 4a). However, the coverage of the London street network by the Blue Book *runs* systematically varies in density with respect to the distribution of *points* and the complexity of the street network: At its boundaries (Figure 4b) this network is less dense than in central London, where the *runs* are also overlapping more often (Figure 4c). This also reflects that more *points* are located closer to the center of London, whereas residential areas are more likely to cover larger regions at the boundaries of the six-mile radius. Similarly, areas of London with a more regular street network, such as in Marylebone and Fitzrovia, are covered by less *runs* (Figure 4d) than areas with a more complex and irregular street network, such as South Kensington and Chelsea (Figure 4e). These might require more practice to learn.

The Blue Book *runs* focus on connecting origin–destination pairs about three miles apart from each other. Since these are mostly main artery roads, they provide the main grid for efficient traveling between those origin–destination pairs. In contrast, minor roads and the areas between the *Oranges and Lemons* (i.e., main roads that are printed in yellow and orange in most maps) are learnt by studying the *quarter-miles* and linking the additional *points* in those areas (Figures 2a and 5b). Further understanding and flexible linking is gained from the Blue Book *runs* as students start considering continuations between them. For instance, one Blue Book *run* would have continued along a sequence of straight streets, but the *run* required a turn off from this straight sequence of streets to reach a destination. In contrast to the previous example, parts of a different *run* might continue straight, where the initial *run* required to turn off the straight sequence of roads. Both examples highlight the importance of the ability to flexibly use individual *runs* as part of the "bigger picture" (interview with K.T., Appendix S1).

Ultimately, they cover large distances across London as such a combination of knowledge enables trainee drivers to link the Blue Book runs efficiently where they intersect, or through minor roads of the quarter miles where no intersection is available (Figure 2c). Over time, links become more efficient as the Knowledge is "ingrained" and minor roads are integrated to create shortcuts where possible. At this point, the Blue Book is no longer perceived as a list of individual routes, but as an entire network of runs (interview with K.T., Appendix S1).

FIGURE 4 Network of Blue Book runs. A visualization of the 320 *runs* that connect the corresponding origin–destination pairs of the Blue Book forms a dense network of routes that overlaps, similar to the quarter mile radii (a). Across the network, density varies and is less dense closer to the six-mile boundary (b) then in Central London (c). This overlap also shows that more routes *run* through areas with higher irregularity in the street network (d) than areas of a more regular street network (e) in Central London *Source*: Adapted from Blue Book mapping by Prof Ed Manley, University of Leeds

4.2 | Learning methods

The progress that *Knowledge* students have to make from learning the first *points* and *runs* to flexibly plan routes all across London is supported through a range of learning techniques as listed in Table 1. These methods can be categorized into theoretical, map-related studies and practical, "in situ" experiences (interview with K.T., Appendix S1; Lordan, 2018). Both support the development of planning strategies that are later used in situations where route planning is required. These include practicing the planning of Blue Book *runs* and general *runs* with a "*call over partner*" (i.e., a *Knowledge school* study partner) in preparation for exams and when driving a taxi as a qualified driver.

In general, maps are used to learn the structure of the street network from a *bird's eye view*. They help obtain knowledge about

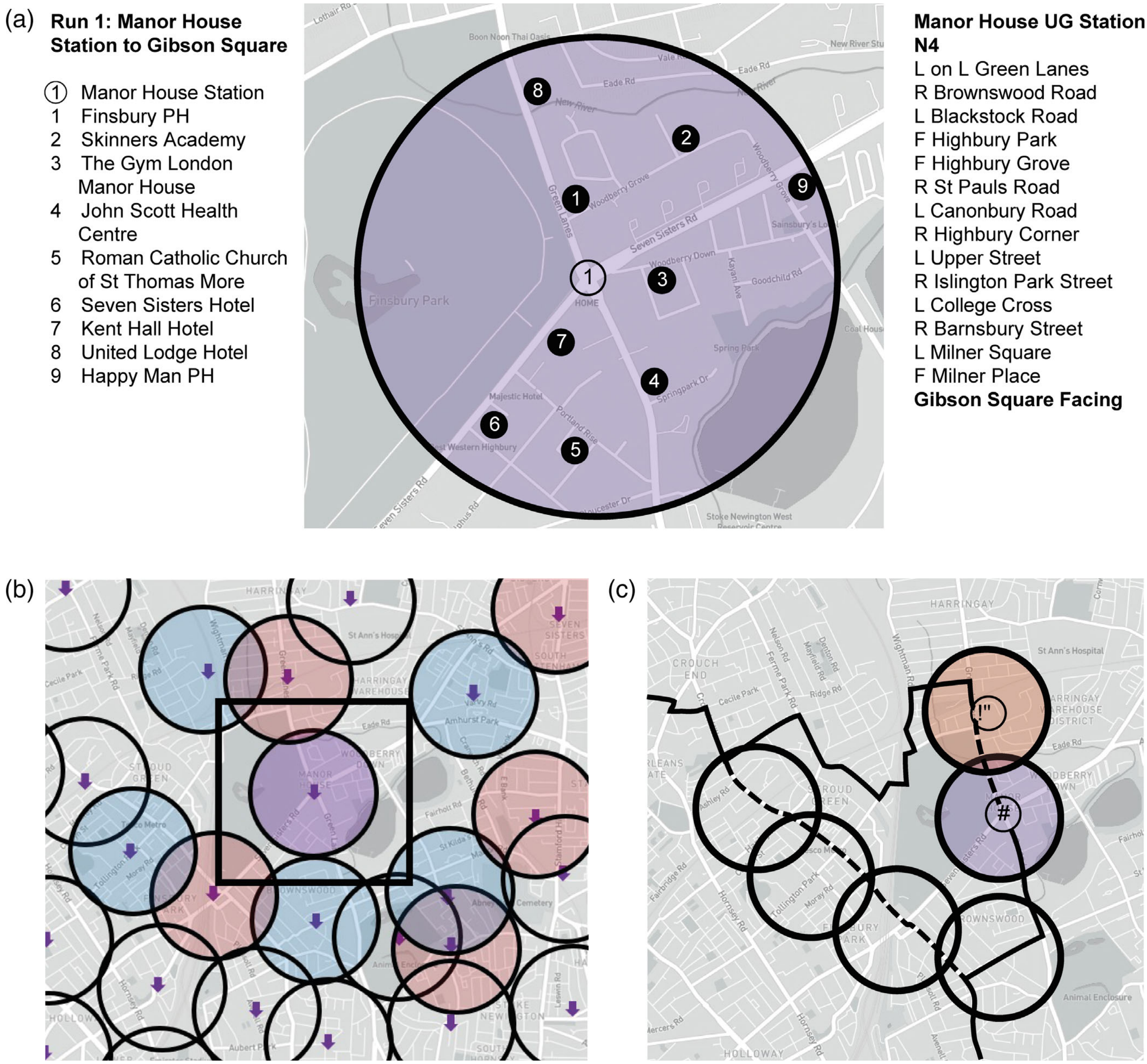

FIGURE 5 The points of the Blue Book. Each origin–destination pair of the Blue Book is presented in relation to its quarter mile area. The origin of a *run*, here *run* 1 (a), Manor House Station, and the corresponding quarter mile radius (black circle) with additional eight other points of interest (numbered 1–8) are marked in a map. Labels are provided in a legend (left) and the most direct route (i.e., "*run*") to the destination, including driving instructions (L on L: leave on left, L: left, R: right; F: forward) are listed on the right. The dense network of origin–destination pairs (b) results in an overlay of the neighboring quarter mile radii (black circles around purple arrows). For Manor House Station (purple circle) neighboring quarter-mile origins and destinations are highlighted in blue and red, respectively. These quarter-miles are covering the six-mile radius in London by linking places of interest through linking *runs* (c) as indicated by the dashed lines connecting *run* 1 (#) from Manor House Station and *run* 80 (!"), ending at Harringay Green Lanes Station. *Source*: Figures are based on learning material from Taxi Trade Promotions

TABLE 1 Learning techniques used in *Knowledge* schools

Learning technique	Supported skill and knowledge
(A) Map study	Bird's eye view:
• General use of maps	• Visualizing street network • Relational knowledge of streets and areas • Areal knowledge (e.g., quarter miles) • Traffic rules (e.g., one-way systems, turning restrictions) • Sequential order of streets
• Dumbbell method[a,b]	• Relational knowledge of places • Areal knowledge
• Linking runs	• Flexible and efficient route planning
• Cottoning up	• Efficient route planning • Relational knowledge of places
• 50% and 75% markers	• Efficient route planning • Relational knowledge of places
• Memory techniques[a]: 1. Acronyms and mnemonics 2. Short stories 3. Method of loci 4. Historical connections 5. Personal connections	• Memorizing groups of streets in consecutive order (1–3) • Relational knowledge of streets in an area (e.g., quarter miles) (4) • Visualizing street network (4) • Relation to personal memories (5)
(B) In situ experience	In-street view
• Traveling in street	• Sequential order of streets • Experience
• Mental simulation	• Visualizing places and streets • Sequential order of streets
(C) Combination of the above	Bird's eye and in-street view
• Call over partner • Practice material • Exam questions	Combination of all to simulate examination and fares

[a]Lordan (2018).
[b]Learn the Knowledge of London.

relations between places and areas (e.g., quarter-miles and boroughs) and learn traffic rules that can limit route planning due to one-way systems and turning restrictions. Additionally, maps facilitate a better understanding of the sequential order of streets that are part of a *run*.

Initially, when studying the *Knowledge*, this information is obtained mainly through the "*dumbbell method*." This requires students to identify the *quarter-miles* of the origin and the destination and visualize the connecting Blue Book *run* by tracing it on the map. By including variations of origins and destinations from the quarter-miles on the map, students start to connect nearby *points* with the original Blue Book origins and destinations and create a network that is forming the "dumbbell" (Figure 3). This method is later extended to other places, as students learn to flexibly link *runs* and cover larger distances across London. This is also supported by the "*cottoning-up*" and the use of subgoals, called the "*50% markers*," which are not included in the blue book and must be determined by the trainee (interview with K.T., Appendix S1). These 50% markers (not always chosen halfway along the direct line) are bridges if the river needs to be crossed to ensure efficient planning through these bottlenecks at early stages, or other major roads and places. Additional subgoals are added before and after, as needed, to help give initial direction for the route planning without overwhelming the students. Both methods, the "*cottoning-up*" and the "*50% markers*," when used during initial stages of the training, help students to correctly visualize the map and relations between places. At a later stage of the *Knowledge*, when route planning is carried out mentally and without a physical map, these methods are integrated in the planning process automatically. Notably, the process involves focusing on distance rather than time between locations. The route with the shortest distance might be extremely slow, but during the training taxi drivers are required to find this route. This relates to the assessment used which uses distance to determine the correct answer (see Section 4.3). After qualifying drivers taxi drivers describe incorporating time into their choice of routes.

To help students memorize sequences of street names that are often used for *runs*, different memory techniques are applied during the learning process and often remembered years after obtaining the license. The most common techniques are creations of acronyms and mnemonics, inventions of short stories that contain street name references, mental walks through rooms of an imaginary house, historical connections and personal memories that logically structure (cf. Table 2, Lordan, 2018). Trainees use the range of techniques in combination to learn, rather than starting with one method and moving to another. Thus, the learning techniques listed in Table 2 provide a set of cognitive tools for learning the layout of London.

Location specific information from an *in-street view* is learnt through "in situ" visits to the 320 origin–destination pairs of the Blue Book, their *quarter-miles* and driving the corresponding *runs*. These visits—carried out multiple times, often on a scooter with a map of the Blue Book *run* attached to the windscreen—are essential to learning and recalling the *Knowledge*. These experiences of runs and the quarter miles create memories that drivers use to later recall sequences of streets (Table 2, Lordan, 2018) and visualize routes during planning (interview with K.T., Appendix S1). For instance, memories of traveling a run for the first time might help the recall of sequences of streets, places of interest and specific traffic rules that must be obeyed. These memories become an essential source of information when planning and calling out similar *runs*, linked to the original. Students use them for mental simulations that facilitate decisions about where to pick up or set down passengers, in which direction to leave or to approach an area and how to find the most optimal route. Thus, students incorporate their study from maps into egocentric representations of directions and turns when driving the runs in situ and this is vital for the planning process. Trainees are not paid so the process of learning is expensive as well as time consuming.

TABLE 2 Common memory techniques to learn runs

Technique name	Example	Streets or places	Run	Book reference
Acronym	"***MEG***"	(1) **M**elton St (2) **E**uston Rd (3) **G**ower St (4) …	121	p. 22
Mnemonic	A: "***b****ask* ***u****nder* ***n****ice* ***f****air* ***w****eather*"	(1) **B**lackfriars Bridge (2) **U**nilever Circus (3) **N**ew Bridge St (4) **F**arringdon St (5) **W**est Smithfield	153	p. 26
	B: "***l****ittle* ***a****pples* ***g****row* ***q****uickly* ***p****lease*"	**L**yric, **A**pollo, **G**ielgud **Q**ueen's, **P**alace (order of Shaftesbury Av theaters)	–	p. 20
Short story	"*In the scary* ***monster film*** (1), *the creatures burst out from behind the closed doors,* ***riling*** (2) *their victims with* ***sheer*** *terror* (3). […]"	(1) Munster Rd, Filmer Rd (2) Rylston Rd, Dawes Rd (3) Sherbrooke Rd (4) …	20	p. 92
Method of loci	"*On the wall of the lobby are several framed* ***certificates*** (1). *Below them is a bookcase where a guide to New York City sticks out, the cover of which is illustrated with an image of Park* ***Avenue*** (2). *A train ticket to* ***Macclesfield*** *is tucked inside as a bookmark* (3). […]"	(1) College Crescent (2) Avenue Rd (3) Macclesfield Bridge (4) …	7	p. 148
History	"*It's believed that Copenhagen House was named either in honor of the King of Denmark or the Danish Ambassador, both of whom stayed there in the 17th century.* *Consequently the first roads on this run have a Danish theme. Matilda Street is named after* ***Queen Caroline Matilda*** *who was born in London but became Queen consort to Denmark after her marriage to Christian VII.* […]"	(1) Matilda St (2) Copenhagen St (3) …	2	p. 106
Experience	"*I remember arriving at* ***Manor House*** *very early one Sunday morning; it was cold and misty and, as I expected many fellow students did, had a brief moment of crisis when I asked myself what on earth I was getting myself into.* *But this thought was quickly expelled when I stood up to stretch my legs – and promptly trod in some dog mess, which in hindsight was probably a symbol of good luck although it certainly did not feel like that at that time.* […]"	(1) Manor House (2) …	1	p. 190

Source: Adapted from Lordan (2018).

4.3 | Assessment scheme

The assessment scheme for trainee taxi drivers in London was designed to support the learning process and guide students from early stages of learning the initial Blue Book *runs* to final stages, where their knowledge of London and suburban artery roads is rigorously challenged (Figure 6; interview with K.T., Appendix S1, Learn the Knowledge of London, Transport for London, n.d.). Initially, *Knowledge schools* offer an introductory class to provide basic information and an overview of the content of the *Knowledge*. This introductory class includes expectations, procedures, and requirements of the qualification process, before preparatory examinations (Figure 6, light gray) can be taken. Within the first 6 months of starting the *Knowledge*, students are expected to sit an assessment that is testing the *Knowledge* on the initial 80 *runs* (five lists) of the Blue Book. Even though this assessment is unmarked, it is obligatory and of supportive and informative purpose at the same time (i.e., formative assessment). Feedback is given and the performance is discussed with teachers to help students identify problems in their learning process that need adjustment at an early stage to enable students to successfully progress at later stages. Following this initial self-assessment, students have 18 months to sit a marked multiple-choice exam that tests their knowledge of the Blue Book, to ensure they have acquired the basics that are necessary to progress to the appearance stages (Figure 6, dark gray). To test this, the multiple-choice exams consist of two parts, where (a) the shortest, legal route out of three possibilities has to be identified for 5 randomly chosen Blue Book *runs*, and (b) the correct location out of six possible locations has to be selected for 25 points of interest that are likely to be part of the learning of the Blue Book *runs*.

After passing the two entry assessments, trainee taxi drivers enter what is known as the "*appearances*," a set of oral examinations. At each *appearance*, students are expected to call *runs* from any two *points* that the examiner names. The *appearances* also comprise the longest and most difficult part of the *Knowledge* examination process.

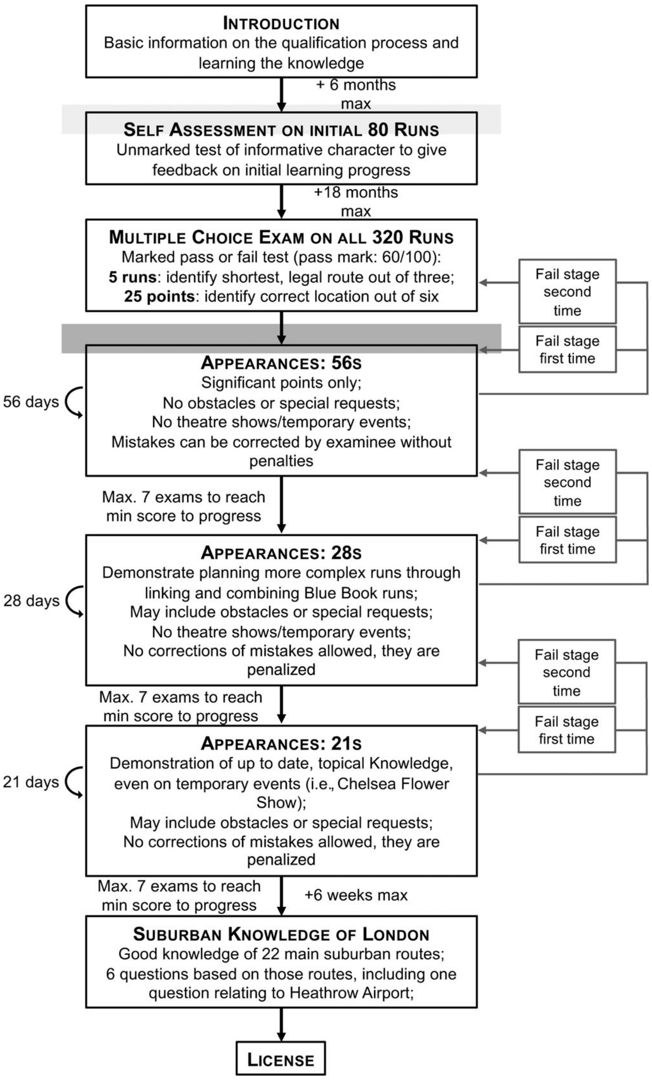

FIGURE 6 Knowledge examination process. The initial stage (light gray) of the *Knowledge* examination process provides feedback (*Self-Assessment*) on the individual progress of learning the first 80 *runs* of the Blue Book and assesses the minimum knowledge on all 320 Blue Book *runs* needed (*Multiple Choice Exam*) to start the oral examination (*Appearances*). The main part of the examination process (dark gray) consists of a series of oral examinations, the so-called "appearances," consisting of three different stages (the 56s, 28s, and 21s, named after the intervals between each exam in the corresponding stage). Even though the requirements to students sitting these exams become more rigorous as they proceed, there are general rules that apply across all stages. These are related to the general layout of each appearance (e.g., duration, number of *runs*), expectations (e.g., shortest route), format of call out (e.g., identifying the location of origin and destination, sequentially naming streets and providing turning instructions), penalties (e.g., traffic rule violations, deviations from shortest route, hesitations), awarded points and progressing to the next stage. Following the appearances, students are required to pass an exam on suburban *Knowledge* before they obtain their license *Source*: Adapted from Learn the Knowledge of London; Knowledge of London learning and examination process, p. 21

It is quite common that several of the stages have to be retaken by students due to shorter intervals between appearances coupled with the growing expectations of the examiners as they proceed. In total, there are three stages of appearances, the 56s, 28s, and 21s, which correspond to the number of days between any two appearances in that stage.

Even though the requirements for students sitting these exams become more rigorous as they proceed, there are general rules that apply across all stages: Each appearance is about 20 min long and can consist of up to 4 *runs* that students have to call, using the shortest route, disregarding traffic and temporary roadworks. The *call outs* (i.e., naming streets in sequential order) include identifying the location (i.e., the correct street) of the origin and destination (points of interest), naming streets and giving turning directions along the *run* in correct sequential order, as well as including instructions for leaving and setting down passengers. Possible errors that will cause deductions of points are incorrect street names, any divergence from the shortest route, violation of traffic rules, impossible leaving or setting down instructions and hesitations during the call of the *run*. In each appearance, 3–6 points are awarded and 12 points are needed to progress to the next stage. Per stage, students are allowed to fail a maximum of three appearances, before the stage has to be repeated (first time) or students have to go back to a previously successfully passed stage (failing second time), limiting the number of exams per stage to a maximum of seven appearances.

In contrast to later appearance stages, the "'56s" are very closely related to the *Knowledge* obtained from the Blue Book. Here, examiners closely stick to *runs* from the Blue Book, which reflects a good knowledge of primary and secondary roads (i.e., the "*oranges and lemons*"). At this stage, examiners also take into account differences in the choice of additional *points* of the quarter-miles that different *Knowledge schools* provide in their version of the Blue Book (Figure 2a). Additionally, *runs* are structured in a way that they will not contain obstacles (e.g., road closures), special requirements (e.g., requests to avoid traffic lights) or theater shows and temporary events (e.g., Chelsea Flower Show). Students are also allowed to correct mistakes by going back in their call out and changing their *run*. At the next stage, the "28s," examinees are expected to be able to link *runs*, using some minor roads and avoid obstacles or comply with special requests without being granted a chance of correcting faulty *runs*. At the final stage, the 21 s, trainee drivers have to demonstrate an overarching knowledge that is up to date and can additionally refer to particular topics (e.g., new tourist attractions, changes in hotel names) and temporary events, such as the Chelsea Flower Show.

After passing all appearances, the final exam is set to test the knowledge of suburban London. This knowledge covers 22 specific routes, including major *points* along those routes, radiating from the six-mile radius to the borough boundaries of London. In this final appearance, trainee drivers will be asked six questions relating to the 22 routes and *points* along those routes.

For the learning process of a *Knowledge* student, the Blue Book is central, as it provides them with "*the ability to know where streets and roads are going to and where all those places are*" (interview with K.T.,

Appendix S1). However, over the course of obtaining the *Knowledge* and learning how to link Blue Book *runs* efficiently, there seems to be a change in the perception of London. Initially it consists of distinct routes and locally focused areas on a map. Over the course of time, this fades into a connected, large-scale, inseparable network of streets and places in the real world (Appendix S1). During consulting conversations with taxi drivers, they reported that they just knew where they had to go without much planning. For well-known places, Robert Lordan described the planning and execution of a *run* as "*I wouldn't even have to think; my brain would be on autopilot*. […] *like a moth drawn to a light!*" (email conversation with Robert Lordan, Appendix S2). For longer distances, subgoals (as trained with the 50% markers) are used automatically: "*I'd find that my brain would often plan in stages; essentially I'd envision a set of waypoints and the route would then come to me as I progressed*" (email conversation with Robert Lordan, Appendix S2).

The overall impact of the *Knowledge* also seems to foster a deeper connection ("*I already loved the city, but in studying it I now love it all the more. It feels like an old, familiar friend*," email conversation with Robert Lordan, Appendix S2). It provides a constant drive to stay up to date with changes in the city ("*The Knowledge made me crave detail! To this day I want to know as much as I can about London*," email conversation with Robert Lordan, Appendix S2) and new curiosity ("*The Knowledge also makes you want to know as much as you can about new locations that you've never been to before*," email conversation with Robert Lordan, Appendix S2).

5 | DISCUSSION

Here we examined the process by which licensed London taxi drivers learn and are examined on the Knowledge of London, which includes the network of ~26,000 streets and thousands of points of interest. In summary, to learn the Knowledge of London, taxi drivers use a wide range of theoretical and practical methods and learn specific methods for efficient planning. Such training primarily includes map-related study, based on an overlapping network of basic points of interest and list of routes (Blue Book) that systematically covers London. This knowledge is combined with visits to the locations used in the routes and retracing of the theoretically learnt routes on motorbikes. Both experiences are reported to be vital for linking theoretically learned information to specific real-world locations and flexible navigation in London. We also observed a range of techniques to improve memory, such as acronyms and stories linked to sequences of streets, visualizing the locations and travel along streets, and the strategic use of subgoals. We discuss: (i) how these findings relate to other studies examining spatial learning, (ii) how the learning compares with taxi drivers in other cities, (iii) why the knowledge is still required and trained when GPS aided navigation systems exist, and (iv) how these methods and techniques might benefit the general population in spatial learning.

Research based studies of spatial navigation have employed a variety of methods to train participants learning unfamiliar environments. These include instructed learning of paths (e.g., Brunec et al., 2017; Meilinger et al., 2008; Meilinger, Frankenstein, & Bülthoff, 2014; Meilinger, Riecke, & Bülthoff, 2014; Wiener et al., 2013), learning from cartographic maps (e.g., Coutrot et al., 2018, 2019; Grison et al., 2017; Hölscher et al., 2006, 2009), landmark-based navigation (e.g., Astur et al., 2005; Newman et al., 2007; Wiener et al., 2004, 2012, 2013; Wiener & Mallot, 2003), exploration of the environment without a map (e.g., de Cothi et al., 2020; Hartley et al., 2003; Spiers, Burgess, Hartley, et al., 2001; Spiers, Burgess, Maguire, et al., 2001) or a combination of map study with in situ exploration (e.g., Javadi et al., 2017; Javadi, Patai, Marin-Garcia, Margois, et al., 2019; Javadi, Patai, Marin-Garcia, Margolis, et al., 2019; Newman et al., 2007; Patai et al., 2019; Spriggs et al., 2018; Warren et al., 2017; Wiener et al., 2004; Wiener & Mallot, 2003). The general assumption is that the method used for learning is efficient, or a standard way of learning the environment. Here we found that for London taxi drivers the training is significantly more intensive and elaborate than any of these studies, which relates to the dramatically increased demands of learning 26,000 streets and thousands of points of interest.

Several methods for learning, such as guided turn-based navigation (e.g., Wiener et al., 2013), have not found an application in the training phase of London taxi drivers. The absence of this approach might be explained through the advantage of in situ experience, understanding the changes with lighting over day time and the very regular changes to the environment (e.g., temporary road closures, name changes of hotels or restaurants, and temporary events). Indeed, being able to adapt to these changes and being aware of some of the temporary events are considered essential knowledge, especially at later stages of the training process.

Successfully recalling mental images of locations, retrieving specific street names and judicious uses of subgoal planning were described as key to being a London taxi driver. These observations help to explain results of by Spiers and Maguire (2008) where London taxi drivers were asked to recall their thoughts watching video replay of their navigation of a highly detailed virtual reality simulation of London. London taxi drivers often reported sequential planning to subgoals along the route, comparison of route alternatives or mental visualizations of places and route sequences. Many taxi drivers reported "picturing the destination," planning with a bird's eye view, and "filling-in" the plan as they navigated, which indicate a use of mental visualization as trained through the Knowledge. We found teachers and examiners claim to know when students "see the points" as they actively visualize origins and destinations as part of their planning process. It may be that trainee taxi drivers need some ability with mental imagery to succeed in the train process. Not all trainees will pass the examination process (Woollett & Maguire, 2011). The ability to use spatial visualization strategies has been found to differ between individuals and vary with age and experience (Salthouse et al., 1990), education levels or gender differences (e.g., Coluccia &

Louse, 2004; Fennema & Sherman, 1977; Moffat et al., 1998; Montello et al., 1999; Wolbers & Hegarty, 2010). There is also evidence that certain spatial visualization skills can be improved through training (Sorby, 2009). In our study we found that it was expected that the visualization improves with the training. Further investigation of the visualization process in novice trainees and expert drivers would be useful and may relate to the changes in the hippocampus observed in those that past the exam to obtain a license (Woollett & Maguire, 2011). The multifaceted learning approach reported here may relate to why changes in gray matter density have consistently been observed in taxi drivers.

Further evidenced use of mental simulation during navigation was found in the way taxi drivers are required to call out the runs in the exam by using instructions and phrases such as "forward," "left/right into," and "comply" (traffic rules). These provide an egocentric description of movement through London. Conversely, during the early stages of the Knowledge training, the planning process is reported to rely on an allocentric reference frame by studying maps to train students on planning shortest paths. At later stages, as experience is gained from planning runs and through in situ visits to locations, the aim is to build an automatic awareness of the direction of travel or a particular route. This is consistent with the reports that experienced taxi drivers very rapidly determined the direction to a requested destination (Spiers & Maguire, 2006a, 2008).

We found that the examination process appears to provide a layered approach to learning the London street network. There is an initial focus on testing the Blue Book routes (runs) or routes along main arterial roads (i.e., "oranges and lemons") and only at later stages are minor roads integrated into the assessments. However, we found the actual learning process requires students to learn minor roads in the quarter-miles from the beginning (i.e., with the first run). This differs from the requirements in other cities, such as Paris, where drivers have to demonstrate knowledge of a limited number of major points of interest, as well as predefined major routes. There, taxi drivers are expected to expand their knowledge to the minor street network through experience while working as a taxi driver (Préfecture de Police, Démarches, & Services, 2020; Skok, 2004). Similar to the "oranges and lemons" of the London street network, the Parisian street network covers the city in two layers: The base network, an uneven grid-like pattern that allows travel on major roads, helps to reduce traffic on the secondary network, a network of minor streets (Chase, 1982; Pailhous, 1969, 1970, 1984). For Parisian taxi drivers, such a selective learning of the base network was found to be also reflected in their mental representation of the street network in form of these two layers (Pailhous, 1969, 1970, 1984). In contrast to London taxi drivers, Parisian taxi drivers' awareness of the secondary network only grows and becomes more efficient and optimal through experience rather than in the training and is almost nonexistent at the beginning of their career (Chase, 1982; Giraudo & Peruch, 1988, 1988b; Peruch et al., 1989).

The approach that London has taken to train and test their taxi drivers on the Knowledge as described above, is historically motivated and has been retained over centuries since its implementation, only allowing for adaptations and improvements. This concept of learning all possible points, their locations, the street names and how to flexibly plan routes and adjust to specific requirements is globally unique. In contrast, other cities, such as Paris (Préfecture de Police, Démarches, & Services, 2020) or Madrid (Federación Profesional del Taxi de Madrid: Departamento de Formación, 2010; Skok & Martinez, 2010), often only require applicants of the trait to learn the major grid of the street network (i.e., the base network) and expect the knowledge of the minor street network (i.e., the secondary network) to be obtained through experience. Instead, taxi drivers are also required to demonstrate knowledge on other trade related areas, such as knowledge related to driving a car, professional regulations, safety and business management, a language test (Skok, 2004), fares and legislations (Skok & Martinez, 2010). Considering these alternative qualification requirements for Paris or Madrid, the London qualification scheme, that relies on a thorough knowledge of London streets, can be questioned as regards to its adequacy and value, in times of GPS systems that can guide navigation.

Given that GPS in general successfully supports navigation and thus is omnipresent in daily life, it remains a key question as to why London taxi drivers continue to rely on their own abilities to plan routes. We found that this to be their sense of accomplishment of a difficult, and in this case, almost impossible task. They often find pride in their ability to master challenging navigation tasks in a complex city only by using their spatial memory independently from external devices that could be sources of mistakes (McKinlay, 2016). This ability to flexibly navigate beyond a base network of major streets, enables London taxi drivers to rapidly follow their route plan even to points in the secondary network, quickly adapt to any changes on-route due to customer preferences or traffic flow (i.e., congestion or road closures) and avoid errors that might result from incorrect instructions given by passengers (e.g., Lordan, 2018). For instance, they might confuse Chelsea's buzzing shopping mile, King's Road, with the quiet King Street near St James's Park, Westminster. These adaptations, that taxi drivers can make instantly, might even outperform GPS systems that sometimes need manual adjustments and additional information input to get to a similar result. In contrast to London, it takes taxi drivers in Paris, Madrid and other cities years to acquire this type of knowledge in their cities and in the end, they might never achieve a similar, highly accurate knowledge of their cities as some areas might be less frequently traveled. Moreover, their experience to filling the gaps in their knowledge might strongly rely on their use of GPS devices, which have been found to impair spatial learning (e.g., Ishikawa et al., 2008) and interfere with spatial navigation (Johnson et al., 2008; McKinlay, 2016). These methods of training taxi drivers might be less efficient and it is thus not surprising that there have been requests from taxi trades of cities like Tokyo, asking London Knowledge teachers to develop a similar method for their taxi schools (interview with K.T., Appendix S1).

How might the Knowledge training process be improved? The Knowledge in its current form, based on the 320 Blue Book runs, has been in place for about two decades, but the study methods have remained the same over many more decades. However, there has been a tendency of involving new technologies and creating online resources, such as apps that can hold and test students on the Blue Book runs. By providing the first plot of all the blue book runs we were able to identify regions in the road network that were poorly sampled and it may be possible for this information to be useful should new routes be required in updating the runs.

It is possible that a database of videos of Blue Book runs would be useful. However, updating this database is a challenge due to the regular change in London's appearance and layout. Online maps and applications could provide a platform that could be regularly updated. Here, the focus could be on Knowledge requirements that allow general contribution, similar to OpenStreetMaps (n.d.), and individual modification, as with Google My Maps (Google Maps. My Maps, n.d.), to support the individual learning process. Such a platform could include updates on points asked in recent appearances that students use for preparation or an option to train with and challenge other students, as well as their call-over partner. Past research has shown it is possible to probe navigation effectively using Google Street View (Brunec et al., 2018, 2019; Patai et al., 2019). However, these platforms would not be able to replace the social situations that students find themselves in at Knowledge schools and when practicing face to face with their call-over partners. These social interactions also have a psychologically motivating, supportive effect. Neither can these digital maps overcome some obvious visual limitations due to screen sizes. These will not allow for a similar view of the "bigger picture" that a wallpaper map is able to convey.

How might the learning process described here be exploited for the general population to learn new places, or emergency workers, or those with wayfinding difficulties caused by a clinical condition? A number of recommendations could be made. One is the focus on street-names. Much navigation in cities can be based on landmarks and the rough knowledge of the area. Recent work has explored how navigation could be improved by enhanced acquisition of landmark knowledge using audio information (Gramann et al., 2017; Wunderlich et al., 2020; Wunderlich & Gramann, 2019). While landmark acquisition is important for navigation (points of interest for the taxi drivers), our analysis of how London taxi drivers learn shows the extra value of learning street names. Learning the street names makes it possible to plan precise paths through the network of streets. This allows for flexible planning that goes beyond chaining sets of landmarks together. This learning can be enhanced by a focus on methods to draw out the street names such as acronyms and rhymes ("East to West Embankment Best"). The memory techniques used in Knowledge schools to memorize sequences of streets such as the "dumbbell method" that links small areas through routes, or mental visualizations of familiar places could initiate new ways of displaying spatial information in maps or GPS devices. A focus on mental imagery is also worth considering in future research to explore how this may benefit new navigation. Finally, teaching a method for efficient planning of longer routes would be a benefit. More research will be required to fully explore these possibilities and understand how they may be integrated with other technology for efficient spatial learning. In such research understanding the order in which information and training is provided would be an important step. Trainee taxi drivers do not have a set order by which they use the different methods, other than the prescribed order in which they learn the blue book runs. Future route guidance systems for learning a new environment might exploit the approach of integrating a set of routes as taxi drivers do here.

Another question arising is how might these discoveries be useful for researchers seeking to build efficient artificial intelligence systems capable of rapid learning and planning? Recent work has explored methods for learning environments and navigating them from street view data or video (Hermann et al., 2020; Mirowski et al., 2016; Xu et al., 2021). The main discoveries here that may be relevant are (1) the organized learning of a set of interconnected routes that allows for flexible planning in the future, (2) the focus on learning a route and then exploring the points at the start and end and then connecting the route to other routes, and (3) learning to create subgoals during the planning process. These approaches to learning may extend not just to improving guidance for how humans learn but for considering the construction of agents that optimally learn structures in the layout of a large city network.

In conclusion, studying the training process of licensed London taxi drivers has provided a useful opportunity to better understand learning strategies and methods that efficiently support the learning process of a large and complex environment. In this observational report, information was gathered on licensed London taxi drivers, who acquire unique spatial knowledge to navigate an enormous street network independently from external support, such as GPS. Forming such mental representations of real-world spaces is essential for the job they perform. Essential strategies include memory techniques, map-based strategies using tactical subgoal selection to improve planning efficiency and mental visualization of places and routes based on experiences. Further research is needed to understand the mental representation that results from these training methods and how this representation affects navigation related planning in brain circuits including the hippocampus.

ACKNOWLEDGMENTS

We thank EPSRC UK and Ordnance Survey for funding our research, Jeremy Morley from Ordnance Survey for supporting this research and his advice during the research. We thank Robert Lorden for his help in developing our research approach with London Taxi drivers. We thank the Knowledge Schools and all the participants for their time and insights. All anonymized data will be made available on request from the corresponding author.

DATA AVAILABILITY STATEMENT

All anonymised data will be made available on request from the corresponding author.

ORCID

Eva-Maria Griesbauer https://orcid.org/0000-0002-9376-2439
Hugo J. Spiers https://orcid.org/0000-0002-6792-6356

REFERENCES

A to Z from Collins—The Knowledge. (2020). Retrieved from https://collins.co.uk/pages/the-knowledge

Astur, R. S., Germain, S. A. S., Baker, E. K., Calhoun, V., Pearlson, G. D., & Constable, R. T. (2005). fMRI hippocampal activity during a virtual radial arm maze. *Applied Psychophysiology and Biofeedback*, *30*(3), 307–317. https://doi.org/10.1007/s10484-005-6385-z

Balaguer, J., Spiers, H., Hassabis, D., & Summerfield, C. (2016). Neural mechanisms of hierarchical planning in a virtual subway network. *Neuron*, *90*(4), 893–903. https://doi.org/10.1016/j.neuron.2016.03.037

Bohbot, V. D., Lerch, J., Thorndycraft, B., Iaria, G., & Zijdenbos, A. P. (2007). Gray matter differences correlate with spontaneous strategies in a human virtual navigation task. *Journal of Neuroscience*, *27*(38), 10078–10083.

Brunec, I. K., Bellana, B., Ozubko, J. D., Man, V., Robin, J., Liu, Z. X., Grady, C., Rosenbaum, R. S., Winocur, G., Barense, M. D., & Moscovitch, M. (2018). Multiple scales of representation along the hippocampal anteroposterior axis in humans. *Current Biology*, *28*(13), 2129–2135.

Brunec, I. K., Javadi, A. H., Zisch, F. E., & Spiers, H. J. (2017). Contracted time and expanded space: The impact of circumnavigation on judgements of space and time. *Cognition*, *166*, 425–432. https://doi.org/10.1016/j.cognition.2017.06.004

Brunec, I. K., Robin, J., Patai, E. Z., Ozubko, J. D., Javadi, A. H., Barense, M. D., Spiers, H. J., & Moscovitch, M. (2019). Cognitive mapping style relates to posterior–anterior hippocampal volume ratio. *Hippocampus*, *29*(8), 748–754.

Burles, F., & Iaria, G. (2020). Behavioural and cognitive mechanisms of developmental topographical disorientation. *Scientific Reports*, *10*(1), 1–11.

Chase, W. G. (1982). Spatial representations of taxi drivers. In *The acquisition of symbolic skills* (pp. 391–405). Springer. https://doi.org/10.1007/978-1-4613-3724-9_43

Chrastil, E. R., Sherrill, K. R., Aselcioglu, I., Hasselmo, M. E., & Stern, C. E. (2017). Individual differences in human path integration abilities correlate with gray matter volume in retrosplenial cortex, hippocampus, and medial prefrontal cortex. *Eneuro*, *4*(2), 1–14.

Clark, I. A., Monk, A. M., Hotchin, V., Pizzamiglio, G., Liefgreen, A., Callaghan, M. F., & Maguire, E. A. (2020). Does hippocampal volume explain performance differences on hippocampal-dependant tasks? *NeuroImage*, *221*, 117211.

Coluccia, E., & Louse, G. (2004). Gender differences in spatial orientation: A review. *Journal of Environmental Psychology*, *24*(3), 329–340. https://doi.org/10.1016/j.jenvp.2004.08.006

Coutrot, A., Manley, E., Yesiltepe, D., Dalton, R. C., Wiener, J. M., Holscher, C., Hornerger, M., & Spiers, H. J. (2020). Cities have a negative impact on navigation ability: Evidence from 38 countries. *preprint*. https://www.biorxiv.org/content/10.1101/2020.01.23.917211v3

Coutrot, A., Schmidt, S., Coutrot, L., Pittman, J., Hong, L., Wiener, J. M., Hoelscher, C., Dalton, R. C., Hornberger, M., & Spiers, H. J. (2019). Virtual navigation tested on a mobile app is predictive of real-world wayfinding navigation performance. *PLoS One*, *14*(3), 1–15. https://doi.org/10.1371/journal.pone.0213272

Coutrot, A., Silva, R., Manley, E., De Cothi, W., Sami, S., Bohbot, V. D., Wiener, J. M., Hoelscher, C., Dalton, R. C., Hornberger, M., & Spiers, H. J. (2018). Global determinants of navigation ability. *Current Biology*, *28*(17), 2861–2866. https://doi.org/10.1016/j.cub.2018.06.009

Dahmani, L., & Bohbot, V. D. (2020). Habitual use of GPS negatively impacts spatial memory during self-guided navigation. *Scientific Reports*, *10*(1), 1–14.

de Cothi, W., Nyberg, N., Griesbauer, E. M., Ghanamé, C., Zisch, F., Lefort, J., Fletcher, L., Newton, C., Renaudineau, S., Bendor, D., Grieves, R., Duvelle, E., Barry, C., & Spiers, H. J. (2020). Predictive maps in rats and humans for spatial navigation. *bioRxiv*, https://doi.org/10.1101/2020.09.26.314815

Ekstrom, A. D., Spiers, H. J., Bohbot, V. D., & Rosenbaum, R. S. (2018). *Human spatial navigation*. Princeton University Press.

Eleanor Cross Knowledge School. (2017). *Blue Book 320 runs only* [PDF file]. http://eleanorcross.net/store/

Electronic blue book—A freedom of information request to transport for London. (2019, January 2). Retrieved from https://www.whatdotheyknow.com/request/electronic_blue_book and https://www.whatdotheyknow.com/request/89944/response/219108/attach/3/Blue%20Book%20All%20London%20no%20cover.pdf

Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans: Spatial navigation and beyond. *Nature Neuroscience*, *20*(11), 1504.

Federación Profesional del Taxi de Madrid: Departamento de Formación. (2010, April 15). Retrieved from https://www.fptaximadrid.es/index.php/formacion

Feld, G. B., Bernard, M., Rawson, A., & Spiers, H. J. (2021). Learning graph networks: Sleep targets highly connected global and local nodes for consolidation. *preprint*. https://www.biorxiv.org/content/10.1101/2021.08.04.455038v1

Fennema, E., & Sherman, J. (1977). Sexual stereotyping and mathematics learning. *The Arithmetic Teacher*, *24*(5), 369–372 www.jstor.org/stable/41189301

Full Set of Blue Book. (2020, May 6). Retrieved from https://www.taxitradepromotions.co.uk/green-badge-blue-book-runs/10002.25.html

Gahnstrom, C. J., & Spiers, H. J. (2020). Striatal and hippocampal contributions to flexible navigation in rats and humans. *Brain and Neuroscience Advances*, *4*, 2398212820979772. https://doi.org/10.1177/2398212820979772

Gardony, A. L., Brunyé, T. T., Mahoney, C. R., & Taylor, H. A. (2013). How navigational aids impair spatial memory: Evidence for divided attention. *Spatial Cognition & Computation*, *13*(4), 319–350. https://doi.org/10.1080/13875868.2013.792821

Giraudo, M. D., & Peruch, P. (1988). Représentation de l'espace urbain et potentiel d'activité du chauffeur de taxi. *Psychologie-Francaise*, *33*(3), 145–150.

Giraudo, M. D., & Peruch, P. (1988b). Spatio-temporal aspects of the mental representation of urban space. *Journal of Environmental Psychology*, *8*(1), 9–17. https://doi.org/10.1016/S0272-4944(88)80020-3

Google Maps. My Maps. (n.d.). Retrieved from https://www.google.co.uk/maps/about/mymaps/

Gramann, K., Hoepner, P., & Karrer-Gauss, K. (2017). Modified navigation instructions for spatial navigation assistance systems lead to incidental spatial learning. *Frontiers in Psychology*, *8*, 193.

Griesbauer, E., Manley, E., McNamee, D., Morley, J., & Spiers, H. J. (2021). What determines a boundary for navigating a complex street network: Evidence from London taxi drivers. *Journal of Navigation*. 1–20. https://doi.org/10.1017/S0373463321000679

Grison, E., Gyselinck, V., Burkhardt, J. M., & Wiener, J. M. (2017). Route planning with transportation network maps: An eye-tracking study. *Psychological Research*, *81*(5), 1020–1034.

Hao, X., Huang, Y., Song, Y., Kong, X., & Liu, J. (2017). Experience with the cardinal coordinate system contributes to the precision of cognitive maps. *Frontiers in Psychology*, *8*, 1166.

Hartley, T., Maguire, E. A., Spiers, H. J., & Burgess, N. (2003). The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. *Neuron*, *37*(5), 877–888.

He, Q., & Brown, T. I. (2020). Heterogeneous correlations between hippocampus volume and cognitive map accuracy among healthy young adults. *Cortex*, *124*, 167–175.

Hejtmánek, L., Oravcová, I., Motýl, J., Horáček, J., & Fajnerová, I. (2018). Spatial knowledge impairment after GPS guided navigation: Eye-tracking study in a virtual town. *International Journal of Human-Computer Studies*, *116*, 15–24. https://doi.org/10.1016/j.ijhcs.2018.04.006

Hermann, K. M., Malinowski, M., Mirowski, P., Banki-Horvath, A., Anderson, K., & Hadsell, R. (2020). Learning to follow directions in street view. *Proceedings of the AAAI Conference on Artificial Intelligence*, *34*(07), 11773–11781.

Hodgetts, C. J., Stefani, M., Williams, A. N., Kolarik, B. S., Yonelinas, A. P., Ekstrom, A. D., Lawrence, A. D., Zhang, J., & Graham, K. S. (2020). The role of the fornix in human navigational learning. *Cortex*, *124*, 97–110.

Hölscher, C., Büchner, S. J., Meilinger, T., & Strube, G. (2009). Adaptivity of wayfinding strategies in a multi-building ensemble: The effects of spatial structure, task requirements, and metric information. *Journal of Environmental Psychology*, *29*(2), 208–219. https://doi.org/10.1016/j.jenvp.2008.05.010

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, *26*(4), 284–299. https://doi.org/10.1016/j.jenvp.2006.09.002

Ishikawa, T., Fujiwara, H., Imai, O., & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology*, *28*(1), 74–82. https://doi.org/10.1016/j.jenvp.2007.09.002

Javadi, A. H., Emo, B., Howard, L. R., Zisch, F. E., Yu, Y., Knight, R., Silva, P. S., & Spiers, H. J. (2017). Hippocampal and prefrontal processing of network topology to simulate the future. *Nature Communications*, *8*(1), 1–11. https://doi.org/10.1038/ncomms14652

Javadi, A. H., Patai, E. Z., Marin-Garcia, E., Margois, A., Tan, H. R. M., Kumaran, D., Nardini, M., Penny, W., Duzel, E., Dayan, P., & Spiers, H. J. (2019). Backtracking during navigation is correlated with enhanced anterior cingulate activity and suppression of alpha oscillations and the 'default-mode' network. *Proceedings of the Royal Society B*, *286*(1908), 20191016. https://doi.org/10.1098/rspb.2019.1016

Javadi, A. H., Patai, E. Z., Marin-Garcia, E., Margolis, A., Tan, H. R. M., Kumaran, D., Nardini, M., Penny, W., Duzel, E., Dayan, P., & Spiers, H. J. (2019). Prefrontal dynamics associated with efficient detours and shortcuts: A combined functional magnetic resonance imaging and magnetoencenphalography study. *Journal of Cognitive Neuroscience*, *31*(8), 1227–1247. https://doi.org/10.1162/jocn_a_01414

Johnson, C. W., Shea, C., & Holloway, C. M. (2008). *The role of trust and interaction in GPS related accidents: A human factors safety assessment of the global positioning system (GPS)*. https://eprints.gla.ac.uk/40172/1/Johnson_Shea_Holloway_GPS.pdf

June 1654: An Ordinance for the Regulation of Hackney-Coachmen in London and the places adjacent (1911). In C. H. Firth & R. S. Rait (Eds.), *Acts and ordinances of the interregnum, 1642–1660* (pp. 922–924). British History Online http://www.british-history.ac.uk/no-series/acts-ordinances-interregnum/pp922-924

Key:highway. (2020, May 1). Retrieved from https://wiki.openstreetmap.org/wiki/Key:highway

Konishi, K., & Bohbot, V. D. (2013). Spatial navigational strategies correlate with gray matter in the hippocampus of healthy older adults tested in a virtual maze. *Frontiers in Aging Neuroscience*, *5*, 1.

Learn the Knowledge of London, Transport for London. (n.d.). Retrieved from https://tfl.gov.uk/info-for/taxis-and-private-hire/licensing/learn-the-knowledge-of-london

Lee, D. W., Miyasato, L. E., & Clayton, N. S. (1998). Neurobiological bases of spatial learning in the natural environment: Neurogenesis and growth in the avian and mammalian hippocampus. *Neuroreport*, *9*(7), R15–R27.

London Metropolitan Archives. (2013, June). Retrieved from https://www.cityoflondon.gov.uk/things-to-do/london-metropolitan-archives/visitor-information/Documents/46-vehicle-registration-and-licensing-records.pdf

Lordan, R. (2018). *The knowledge: Train your brain like a cabbie*. Quercus.

Maguire, E. A., Frackowiak, R. S., & Frith, C. D. (1997). Recalling routes around London: Activation of the right hippocampus in taxi drivers. *Journal of Neuroscience*, *17*(18), 7103–7110. https://doi.org/10.1523/JNEUROSCI.17-18-07103

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, *97*(8), 4398–4403. https://doi.org/10.1073/pnas.070039597

Maguire, E. A., Nannery, R., & Spiers, H. J. (2006). Navigation around London by a taxi driver with bilateral hippocampal lesions. *Brain*, *129*(11), 2894–2907. https://doi.org/10.1093/brain/awl286

Maguire, E. A., Spiers, H. J., Good, C. D., Hartley, T., Frackowiak, R. S., & Burgess, N. (2003). Navigation expertise and the human hippocampus: A structural brain imaging analysis. *Hippocampus*, *13*(2), 250–259.

Maguire, E. A., Woollett, K., & Spiers, H. J. (2006). London taxi drivers and bus drivers: A structural MRI and neuropsychological analysis. *Hippocampus*, *16*(12), 1091–1101. https://doi.org/10.1002/hipo.20233

Mapbox. (2020). Retrieved from https://www.mapbox.com/

McKinlay, R. (2016). Technology: Use or lose our navigation skills. *Nature*, *531*(7596), 573–575. https://doi.org/10.1038/531573a

Meilinger, T., Frankenstein, J., & Bülthoff, H. H. (2014). When in doubt follow your nose—A wayfinding strategy. *Frontiers in Psychology*, *5*, 1363. https://doi.org/10.3389/fpsyg.2014.01363

Meilinger, T., Knauff, M., & Bülthoff, H. H. (2008). Working memory in wayfinding—A dual task experiment in a virtual city. *Cognitive Science*, *32*(4), 755–770. https://doi.org/10.1080/03640210802067004

Meilinger, T., Riecke, B. E., & Bülthoff, H. H. (2014). Local and global reference frames for environmental spaces. *The Quarterly Journal of Experimental Psychology*, *67*(3), 542–569. https://doi.org/10.1080/17470218.2013.821145

Mirowski, P., Pascanu, R., Viola, F., Soyer, H., Ballard, A. J., Banino, A., Denil, M., Goroshin, R., Sifre, L., Kavukcuoglu, K., Kumaran, D., & Hadsell, R. (2016). *Learning to navigate in complex environments*. arXiv preprint arXiv:1611.03673.

Moffat, S. D., Hampson, E., & Hatzipantelis, M. (1998). Navigation in a "virtual" maze: Sex differences and correlation with psychometric measures of spatial ability in humans. *Evolution and Human Behavior*, *19*(2), 73–87. https://doi.org/10.1016/S1090-5138(97)00104-9

Montello, D. R., Lovelace, K. L., Golledge, R. G., & Self, C. M. (1999). Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers*, *89*(3), 515–534. https://doi.org/10.1111/0004-5608.00160

Morris, R. G., Garrud, P., Rawlins, J. A., & O'Keefe, J. (1982). Place navigation impaired in rats with hippocampal lesions. *Nature*, *297*(5868), 681–683.

Münzer, S., Zimmer, H. D., & Baus, J. (2012). Navigation assistance: A trade-off between wayfinding support and configural learning support. *Journal of Experimental Psychology: Applied*, *18*(1), 18. https://doi.org/10.1037/a0026553

Münzer, S., Zimmer, H. D., Schwalm, M., Baus, J., & Aslan, I. (2006). Computer-assisted navigation and the acquisition of route and survey knowledge. *Journal of Environmental Psychology*, *26*(4), 300–308. https://doi.org/10.1037/a0026553

Newcombe, N. S. (2018). Individual variation in human navigation. *Current Biology*, *28*(17), R1004–R1008.

Newman, E. L., Caplan, J. B., Kirschen, M. P., Korolev, I. O., Sekuler, R., & Kahana, M. J. (2007). Learning your way around town: How virtual taxicab drivers learn to use both layout and landmark information.

Cognition, *104*(2), 231–253. https://doi.org/10.1016/j.cognition.2006.05.013

Newton, R. (1857). In S. Urban (Ed.), *The omnibuses of London*. The Gentleman's Magazine.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Clarendon Press ISBN: 0-19-857206-9.

OpenStreetMaps. (n.d.). Retrieved from https://www.openstreetmap.org/about

OS MasterMap Integrated Transport Network (ITN) Layer. Coverage: London. (2018, October). *Ordnance Survey, GB. Using: EDINA Digimap Ordnance Survey Service*. https://digimap.edina.ac.uk/

Pailhous, J. (1969). Représentation de l'espace urbain et cheminements. *Le travail humain*, 87–139.

Pailhous, J. (1970). *La représentation de l'espace urbain: l'exemple du chauffeur de taxi*. Presses Universitaires de France.

Pailhous, J. (1984). The representation of urban space: its development and its role in the organisation of journeys. In: *Social representations* (Farr, RM, Moscovici, S, eds), pp 311–327. Cambridge, England: Cambridge UP.

Patai, E. Z., Javadi, A. H., Ozubko, J. D., O'Callaghan, A., Ji, S., Robin, J., Grady, C., Winocur, G., Rosenbaum, R. S., Moscovitch, M., & Spiers, H. J. (2019). Hippocampal and retrosplenial goal distance coding after long-term consolidation of a real-world environment. *Cerebral Cortex*, *29*(6), 2748–2758. https://doi.org/10.1093/cercor/bhz044

Peruch, P., Giraudo, M. D., & Garling, T. (1989). Distance cognition by taxi drivers and the general public. *Journal of Environmental Psychology*, *9*(3), 233–239. https://doi.org/10.1016/S0272-4944(89)80037-4

Préfecture de Police, Démarches & Services. *Vous souhaitez devenir conducteur de taxi*. (2020). https://www.prefecturedepolice.interieur.gouv.fr/Demarches/Professionnel/Transports/Taxis-parisiens/Vous-souhaitez-devenir-conducteur-de-taxi

Rosen, J. & (2014, November 10). The Knowledge, London's Legendary Taxi-Driver Test Puts Up a Fight in the Age of GPS. Retrieved from https://www.nytimes.com/2014/11/10/t-magazine/london-taxi-test-knowledge.html

Ruginski, I. T., Creem-Regehr, S. H., Stefanucci, J. K., & Cashdan, E. (2019). GPS use negatively affects environmental learning through spatial transformation abilities. *Journal of Environmental Psychology*, *64*, 12–20.

Salthouse, T. A., Babcock, R. L., Skovronek, E., Mitchell, D. R., & Palmon, R. (1990). Age and experience effects in spatial visualization. *Developmental Psychology*, *26*(1), 128. https://doi.org/10.1037/0012-1649.26.1.128

Schinazi, V. R., Nardi, D., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2013). Hippocampal size predicts rapid learning of a cognitive map in humans. *Hippocampus*, *23*(6), 515–528.

Sherrill, K. R., Chrastil, E. R., Aselcioglu, I., Hasselmo, M. E., & Stern, C. E. (2018). Structural differences in hippocampal and entorhinal gray matter volume support individual differences in first person navigational ability. *Neuroscience*, *380*, 123–131.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In *Advances in child development and behavior* (Vol. 10, pp. 9–55). JAI. https://doi.org/10.1016/S0065-2407(08)60007-5

Skok, W. (1999). Knowledge management: London taxi cabs case study. In *Proceedings of the 1999 ACM SIGCPR conference on computer personnel research* (pp. 94–101). https://doi.org/10.1145/299513.299625

Skok, W. (2004). Knowledge management: Taxis Parisiens case study. *Knowledge Management Research & Practice*, *2*(3), 147–154. https://doi.org/10.1057/palgrave.kmrp.8500035

Skok, W., & Martinez, J. A. (2010). An international taxi cab evaluation: Comparing Madrid with London, New York, and Paris. *Knowledge and Process Management*, *17*(3), 145–153. https://doi.org/10.1002/kpm.346

Smulders, T. V., Sasson, A. D., & DeVoogd, T. J. (1995). Seasonal variation in hippocampal volume in a food-storing bird, the black-capped chickadee. *Journal of Neurobiology*, *27*(1), 15–25.

Sorby, S. A. (2009). Developing 3-D spatial visualization skills. *Engineering Design Graphics Journal*, *63*(2), 21–33.

Spiers, H. J., Burgess, N., Hartley, T., Vargha-Khadem, F., & O'Keefe, J. (2001). Bilateral hippocampal pathology impairs topographical and episodic memory but not visual pattern matching. *Hippocampus*, *11*(6), 715–725.

Spiers, H. J., Burgess, N., Maguire, E. A., Baxendale, S. A., Hartley, T., Thompson, P. J., & O'Keefe, J. (2001). Unilateral temporal lobectomy patients show lateralized topographical and episodic memory deficits in a virtual town. *Brain*, *124*(12), 2476–2489.

Spiers, H. J., & Maguire, E. A. (2006a). Thoughts, behaviour, and brain dynamics during navigation in the real world. *NeuroImage*, *31*(4), 1826–1840. https://doi.org/10.1016/j.neuroimage.2006.01.037

Spiers, H. J., & Maguire, E. A. (2006b). Spontaneous mentalizing during an interactive real world task: An fMRI study. *Neuropsychologia*, *44*(10), 1674–1682.

Spiers, H. J., & Maguire, E. A. (2007a). A navigational guidance system in the human brain. *Hippocampus*, *17*(8), 618–626. https://doi.org/10.1002/hipo.20298

Spiers, H. J., & Maguire, E. A. (2007b). Neural substrates of driving behaviour. *NeuroImage*, *36*(1), 245–255.

Spiers, H. J., & Maguire, E. A. (2008). The dynamic nature of cognition during wayfinding. *Journal of Environmental Psychology*, *28*(3), 232–249. https://doi.org/10.1016/j.jenvp.2008.02.006

Spriggs, M. J., Kirk, I. J., & Skelton, R. W. (2018). Hex maze: A new virtual maze able to track acquisition and usage of three navigation strategies. *Behavioural Brain Research*, *339*, 195–206. https://doi.org/10.1016/j.bbr.2017.11.041

Stevens, A., & Coupe, P. (1978). Distortions in judged spatial relations. *Cognitive Psychology*, *10*(4), 422–437. https://doi.org/10.1016/0010-0285(78)90006-3

Streeter, L. A., & Vitello, D. (1986). A profile of drivers' map-reading abilities. *Human Factors*, *28*(2), 223–239. https://doi.org/10.1177/001872088602800210

The London Taxi Experience—The Knowledge. (2020). Retrieved from http://www.the-london-taxi.com/london_taxi_knowledge

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189–208. https://doi.org/10.1037/h0061626

Warren, W. H., Rothman, D. B., Schnapp, B. H., & Ericson, J. D. (2017). Wormholes in virtual space: From cognitive maps to cognitive graphs. *Cognition*, *166*, 152–163. https://doi.org/10.1016/j.cognition.2017.05.020

Weisberg, S. M., & Ekstrom, A. D. (2021). Hippocampal volume and navigational ability: The map (ping) is not to scale. *Neuroscience & Biobehavioral Reviews*, *126*, 102–112.

Weisberg, S. M., & Newcombe, N. S. (2016). How do (some) people make a cognitive map? Routes, places, and working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(5), 768.

Weisberg, S. M., Newcombe, N. S., & Chatterjee, A. (2019). Everyday taxi drivers: Do better navigators have larger hippocampi? *Cortex*, *115*, 280–293.

Weisberg, S. M., Schinazi, V. R., Newcombe, N. S., Shipley, T. F., & Epstein, R. A. (2014). Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(3), 669.

Wiener, J. M., de Condappa, O., Harris, M. A., & Wolbers, T. (2013). Maladaptive bias for extrahippocampal navigation strategies in aging humans. *Journal of Neuroscience*, *33*(14), 6012–6017. https://doi.org/10.1523/JNEUROSCI.0717-12.2013

Wiener, J. M., Kmecova, H., & de Condappa, O. (2012). Route repetition and route retracing: Effects of cognitive aging. *Frontiers in Aging Neuroscience*, *4*, 7. https://doi.org/10.3389/fnagi.2012.00007

Wiener, J. M., & Mallot, H. A. (2003). 'Fine-to-coarse' route planning and navigation in regionalized environments. *Spatial Cognition* *and Computation*, *3*(4), 331–358. https://doi.org/10.1207/s15427633scc0304_5

Wiener, J. M., Schnee, A., & Mallot, H. A. (2004). Use and interaction of navigation strategies in regionalized environments. *Journal of Environmental Psychology*, *24*(4), 475–493. https://doi.org/10.1016/j.jenvp.2004.09.006

Wolbers, T., & Hegarty, M. (2010). What determines our navigational abilities? *Trends in Cognitive Sciences*, *14*(3), 138–146. https://doi.org/10.1016/j.tics.2010.01.001

Woollett, K., Glensman, J., & Maguire, E. A. (2008). Non-spatial expertise and hippocampal gray matter volume in humans. *Hippocampus*, *18*(10), 981–984.

Woollett, K., & Maguire, E. A. (2009). Navigational expertise may compromise anterograde associative memory. *Neuropsychologia*, *47*(4), 1088–1095. https://doi.org/10.1016/j.neuropsychologia.2008.12.036

Woollett, K., & Maguire, E. A. (2011). Acquiring "the Knowledge" of London's layout drives structural brain changes. *Current Biology*, *21*(24), 2109–2114. https://doi.org/10.1016/j.cub.2011.11.018

Woollett, K., & Maguire, E. A. (2012). Exploring anterograde associative memory in London taxi drivers. *Neuroreport*, *23*(15), 885. https://doi.org/10.1097/WNR.0b013e328359317e

Woollett, K., Spiers, H. J., & Maguire, E. A. (2009). Talent in the taxi: A model system for exploring expertise. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1522), 1407–1416. https://doi.org/10.1098/rstb.2008.0288

Wunderlich, A., & Gramann, K. (2019). Overcoming spatial deskilling using landmark-based navigation assistance systems. *preprint*, 789529. https://www.biorxiv.org/content/10.1101/789529v3

Wunderlich, A., Grieger, S., & Gramann, K. (2020). Landmark-based turn-by-turn instructions enhance incidental spatial knowledge acquisition. *bioRxiv*. https://www.biorxiv.org/content/10.1101/2020.11.30.403428v1

Xu, M., Fischer, T., Sünderhauf, N., & Milford, M. (2021). Probabilistic appearance-invariant topometric localization with new place awareness. *IEEE Robotics and Automation Letters*, *6*(4), 6985–6992.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Griesbauer, E.-M., Manley, E., Wiener, J. M., & Spiers, H. J. (2022). London taxi drivers: A review of neurocognitive studies and an exploration of how they build their cognitive map of London. *Hippocampus*, *32*(1), 3–20. https://doi.org/10.1002/hipo.23395