JOURNAL OF LOCATION BASED SERVICES
https://doi.org/10.1080/17489725.2018.1508763

Location based services: ongoing evolution and research agenda

Haosheng Huang [a], Georg Gartner [b], Jukka M. Krisp [c], Martin Raubal [d] and Nico Van de Weghe [e]

[a]GIScience Center, Department of Geography, University of Zurich, Zurich, Switzerland; [b]Research Group Cartography, Department of Geodesy and Geoinformation, TU Wien, Vienna, Austria; [c]Research Group Applied Geoinformatics, University of Augsburg, Augsburg, Germany; [d]Institute of Cartography and Geoinformation, ETH Zurich, Zurich, Switzerland; [e]Department of Geography, Ghent University, Ghent, Belgium

ABSTRACT
We are now living in a mobile information era, which is fundamentally changing science and society. Location Based Services (LBS), which deliver information depending on the location of the (mobile) device and user, play a key role in this mobile information era. This article first reviews the ongoing evolution and research trends of the scientific field of LBS in the past years. To motivate further LBS research and stimulate collective efforts, this article then presents a series of key research challenges that are essential to advance the development of LBS, setting a research agenda for LBS to 'positively' shape the future of our mobile information society. These research challenges cover issues related to the core of LBS development (e.g. positioning, modelling, and communication), evaluation, and analysis of LBS-generated data, as well as social, ethical, and behavioural issues that rise as LBS enter into people's daily lives.

ARTICLE HISTORY
Received 4 April 2018
Accepted 18 July 2018

KEYWORDS
Location based services; research trends; research agenda; mobile devices; context-aware computing

1. Introduction

While the first location based services (LBS) appeared in the early 1990s (e.g. ActiveBadge), LBS became a fast-developing research field only in the early 2000s, mainly due to the discontinuation of the selective availability[1] of Global Positioning System (GPS) by the U.S. President Bill Clinton in May 2000. This discontinuation has made GPS more responsive to civil and commercial users worldwide. Since that time, more and more GPS-based applications have appeared, resulting in a strong interest in LBS from both academics and industry. LBS can be defined as computer applications (especially mobile computing applications) that deliver information tailored to the location and context of the device and the user (Raper et al. 2007a; Brimicombe and Chao 2009). In 2007, Raper et al. (2007a, 2007b) provided a state-of-the-art review of the research field of LBS, and outlined several research challenges. Since then, there have been many changes in the field. First, recent years have witnessed rapid advances in its enabling technology, such as mobile devices and telecommunication. Second, there has been an increasing demand in expanding LBS

CONTACT Haosheng Huang haosheng.huang@geo.uzh.ch

from outdoors to indoors, and from navigation systems and mobile guides to more diverse applications (e.g. healthcare, transportation, and gaming). Third, new interface technologies (e.g. more powerful smartphones, smartwatches, digital glasses, and augmented reality (AR) devices) have emerged. Fourth, there has been an increasing smartness of our environments and cities (e.g. with different kinds of sensors) (Ratti and Claudel 2016). And, finally, we have seen more and more LBS entering into the general public's daily lives, which greatly influence how people interact with each other and their behaviours in different environments. It also brings many opportunities (e.g. for traffic management and urban planning) and challenges (e.g. privacy, ethical, and legal issues) to our environment and human society. These changes open up a lot of basic and applied research questions to the LBS research community.

In this article, we review the ongoing evolution in LBS and suggest a new research agenda for the domain of LBS, with the aim of motivating further LBS research and stimulate collective efforts. Besides the persistent challenges in LBS that were already outlined in previous LBS research agendas (Raper et al. 2007a; Jiang and Yao 2006), we focus here on new challenges raised in recent years. To identify the key research questions and challenges that are essential for the further development in LBS, we followed a multi-phase collaborative process. The majority of the LBS research community (especially members of the International Cartographic Association (ICA) Commission on LBS) was invited to write a one-paragraph proposal to describe what they believed were the 'big challenges' that should be addressed in order to bring LBS to a higher level, and why. In total, 31 proposals from experts in various disciplines, such as GIScience, cartography, geomatics, surveying, computer science, and social sciences were received covering different aspects of LBS research. These proposals were then compiled and grouped into a first list of 'key challenges', which was circulated to get comments and feedback. A workshop at the LBS 2016 conference (http://lbs2016.lbsconference.org/) and a dedicated session at the ICC 2017 conference (http://icc2017.org/) were organised to iteratively refine and elaborate these 'key challenges'. Feedback and results of these meetings were carefully considered and integrated, which led to the open questions and opportunities described in this agenda.

LBS is a field which currently attracts a lot of commercial interest in parallel, typically having a different focus than in academics. This research agenda does not aim to cover these, but rather focuses on the academic perspectives. As Raper et al. (2007a, 6) mentioned, in broad terms researchers can 'envisage and embody "blue sky" innovations; explore user experiences and social implications outside commercial implementation; tackle technical problems that lead to system developments without an early return'. In this article, we focus on fundamental issues (either technical or non-technical) that make LBS smarter and more acceptable by the users, as well as on the social implications brought by LBS.

Our research agenda contributes to the research efforts to 'positively' shape the future of the mobile information society, into which our society is evolving. With the integration of information and communication technologies (ICT), especially mobile ICT in every aspect of our daily lives, 4A (anytime, anywhere, for anyone and anything) 'services' are being developed to benefit our human society and environment. This new generation of 4A technologies brings convenience and improves our quality of life, but also leads to surveillance, privacy and ethical issues, unknown, and unimagined before. It is therefore important to investigate how these technologies influence the way we grow, interact, socialise, and learn. This research agenda also aims to contribute to advancing the use of geospatial information and technologies in our society.

In the following, we begin by reviewing the ongoing evaluation of LBS research in recent years (Section 2). In Section 3, the research agenda is elaborated, highlighting the challenges and potential opportunities that help to address these challenges. In Section 4, we summarise the scientific domain of LBS, as well as question about whether there exists a Location Based Science (LBScience). Finally, in Section 5, we conclude this article and explore how the research community can work together to bring LBS to a higher level.

2. Ongoing evolution of LBS research

In the first two issues of the Journal of Location Based Services, Raper et al. (2007a, 2007b) provided a critical review of the research field of LBS. Recent years have witnessed rapid advances in LBS with the continuous evolvement of mobile devices and communication technologies. Research on LBS has been approached from different disciplines and different perspectives. In the following, we review the key trends in the LBS domain over the last 10 years, mainly on the aspects of application domains, application environments (outdoor and indoor), context-awareness, user interfaces, evaluation, and analysis of LBS data.

2.1. *More diverse applications*

In 2007, Raper et al. (2007b) provided a comprehensive review on the application fields of LBS. They showed that mobile guides and navigation systems (e.g. car navigation systems and pedestrian navigation systems) were the largest groups of LBS applications. Mobile guides can be considered as 'portable, location-sensitive and information-rich digital guides to the user's surroundings'. They often provide functionalities, such as mobile search, 'you-are-here' maps, and tour guides for tourism and recreational purposes. Navigation systems (e.g. for car drivers or pedestrians) are designed to assist in people's wayfinding tasks in unfamiliar environments. While mobile guides and navigation systems continue to be some of the main LBS applications and are still being improved (e.g. landmark-based navigation and inclusion of real-time traffic information) (Krisp and Keler 2015), more diverse LBS applications have been emerging and becoming more mature in recent years (Figure 1).

In the following we introduce some of the main ones:

- **Location based social networks (LBSN)**. The increasing availability of location-aware technology (e.g. GPS) enables people to add a location dimension to existing online social networks in various ways, e.g. uploading geotagged contents (e.g. photos, videos, and recorded routes), sharing the present location (e.g. 'check-in' at Foursquare), commenting on an event at the place where it is happening (e.g. via Twitter), or leaving ratings/tips/reviews for a location (e.g. a restaurant) (Zheng 2011). Examples of mobile LBSN applications include Foursquare, Facebook, Google+, Twitter, and Instagram. These applications allow end users to share information with friends, connect with friends and get alerted when they are nearby, explore places and events in the real world, and receive location based advertisements. While these applications are mostly developed by companies, many research studies utilise the user-generated contents of these applications for making (location) recommendations

Figure 1. Example application domains of LBS.

(Huang 2016; Bao et al. 2015), modelling individual and crowd mobility, understanding the dynamics and semantics of cities (Gao, Janowicz, and Couclelis 2017) and detecting and managing real-time events (e.g. disasters) (Atefeh and Khreich 2015).

- **Location based gaming (LBG)**. Typically, LBG maps real world environments into a virtual world, where players must move themselves in real life to explore the virtual world and accomplish tasks related to the game itself (Maia et al. 2017). The maps, tasks, and other contents presented on the mobile devices are adapted to the location of the player. According to the game objectives, players may collect virtual objects, such as weapons, ammunition, or treasures. These objects can be used to achieve benefits in the virtual world, or even in the real world. Examples of popular LBG include Geocaching, Ingress, and Pokémon Go.
- **Location based fitness monitoring and healthcare**. Another rapidly growing group of LBS applications focuses on healthcare, particularly on outdoor exercise and fitness monitoring (e.g. Running app, Moves, and Runkeeper), remote health monitoring supporting dementia patients and their caregivers in wandering events (Herrera 2017), and emergency situation detecting and reporting (e.g. fall detection) (Horta, Lopes, and Rodrigues 2015). For the first type of application (i.e. fitness monitoring), gamification techniques and social networking aspects are often used to motivate and promote physical activities and healthy living styles. In addition to location-tracking technologies, these applications often make use of other sensors available on smartphones, such as accelerometers and pedometers. In recent years, there has been a trend on combining LBS with other wearable sensors (e.g. for sensing heart rate, blood pressure, EEG signal, and body temperature) for health monitoring, and providing personalised health-care information and services (Adibi 2015).

- **Transport LBS**. By tradition, transport has been one of the main application fields of LBS. Applications include those for driver assistance, passenger information, and vehicle management (Raper et al. 2007b). Car navigation systems are probably the most popular LBS applications, which provide wayfinding assistance for drivers, and are still being improved with new features, such as real-time traffic information. For example, Waze (https://www.waze.com/) crowdsources traffic and road information to provide drivers with real-time navigation supports. LBS and tracking techniques have now been extensively used for vehicle management and logistic tracking. In recent years, applications beyond car navigation and vehicle management have been emerging. For example, for driver assistance and passenger guidance, applications for finding available on-street parking spaces (e.g. Parkbob http://www.parkbob.com/), safety warning (Y. Li, Wang, and Zhang 2015), multimodal routing (Bucher, Jonietz, and Raubal 2017) have appeared. There are also studies using LBS to promote more healthy, greener (lower CO_2 emission), and more active mobility behaviours (Bucher et al. 2016).
- **Location based assistive technology**. LBS are also being used as assistive technology to enable visually impaired people, and disabled and elderly people to perform their daily living activities independently and to experience an improved quality of life (Hakobyan et al. 2013). These assistive systems provide assisted-living functions, such as personalised navigation and wayfinding (Stepnowski, Kamiński, and Demkowicz 2011), obstacle detection (Peng et al. 2010), space perception (Shen et al. 2008), and independent shopping (Eduardo et al. 2017). With the increasingly aging population, one can expect that more and more location based assistive systems will be developed and employed in the future.

Recent years have also seen the application domains of LBS being expanded into disaster and emergency (Choy et al. 2016), supporting citizens' involvements in society (e.g. for crime mapping, reporting urban problems), education (learning in the field) (Sailer et al. 2016), entertainment (e.g. music) (Åman, Liikkanen, and Hinkka 2015), insurance (Pham et al. 2016), billing (Kozlovsky, Dvorak, and Krejcar 2016), and supporting production processes in factories (Jo et al. 2017). While most LBS applications are developed primarily for supporting individual users, some researchers have started to develop LBS applications to support groups of users for collaborative task solving (Espeter and Raubal 2009), such as wayfinding and museum visiting (Reilly et al. 2009; Lanir et al. 2016).

2.2. *From outdoor to indoor and mixed outdoor/indoor environments*

In the early 2000s, research on LBS had been mainly focused on outdoor environments, also due to the lack of reliable indoor positioning methods, as well as the lack of indoor GIS data (Raper et al. 2007a, 2007b). In recent years, LBS have become more and more popular not only in outdoor environments, but also in shopping malls, museums, airports, many other indoor environments, and even mixed outdoor/indoor environments. This is mainly due to the advancements in indoor positioning and indoor spatial data modelling and the increasing availability of indoor GIS data in the last decade.

Different location sensor technologies have been developed and tested for estimating the location of a smartphone in indoor environments (Davidson and Piche 2017), such as WiFi (Retscher and Roth 2017), RFID (Bai 2016), Bluetooth (Huang et al. 2009), NFC

(Ozdenizci, Coskun, and Kerem 2015), and UWB (Alarifi et al. 2016). Positioning methods, such as proximity sensing, lateration, dead reckoning, and pattern matching (e.g. fingerprinting) were employed. Among them, WiFi-based fingerprinting has attracted a lot of research interest, and likely represents the "state-of-the-art" in indoor positioning (Davidson and Piche 2017). Bluetooth Low Energy (BLE) beacons, such as Apple's iBeacon, Google's URIBeacon and Eddystone, and Radius Networks' AltBeacon, are also often employed for indoor positioning, using their 'proximity' mode (Davidson and Piche 2017). To improve position accuracy, map-matching using building floor plans, as well as signal fusion with other sensors (e.g. accelerometer, gyroscope, and magnetometer) have been proposed (Lam, Tang, and Grundy 2016).

As mentioned before, recent years have also seen rapid advances in indoor spatial data modelling, as well as the increasing availability of indoor GIS data. A number of indoor space models have been developed (Afyouni, Ray, and Claramunt 2017), from 3D building models, such as cityGML (Gröger and Lutz 2012) and Building Information Modelling BIM (Isikdag and Zlatanova 2009), over polygonal approaches (Slingsby and Raper 2008) to network solutions like Geometric Network Model (GNM) (Lee 2004), corridor derivation, cell-decomposed networks (Lorenz, Ohlbach, and Stoffel 2006), and visibility-based models. Recently, the Open Geospatial Consortium (OGC) approved a new standard IndoorGML for the representation and exchange of geoinformation for indoor applications (Lee et al. 2014), with GNM as the underlying network. OpenStreetMap also introduced an indoor tagging schema for indoor mapping (https://wiki.openstreetmap.org/wiki/Proposed_features/IndoorOSM), which can be used to model different floor levels, different indoor elements (e.g. rooms, areas, walls, and corridors), and connections between different elements. In recent years, research has also paid attention to connecting outdoor and indoor environments (Vanclooster, Van de Weghe, and Philippe 2016; Yang and Worboys 2011).

These rapid advances in indoor positioning and indoor data modelling have triggered many innovative indoor LBS applications, such as indoor navigation/wayfinding (Fellner, Huang, and Gartner 2017), guides at museums/exhibitions (Kaulich, Heine, and Kirsch 2017), emergency response (Zhao, Winter, and Tomko 2017), shopping guides (Eduardo et al. 2017), and location based advertisement (Mathew et al. 2017). Typical venues of indoor LBS applications include universities/schools, museums, complex transport hubs (e.g. airports and train/subway stations), and shopping malls.

2.3. *Towards context-awareness*

As the term suggests, location plays an essential role in LBS as it determines the services and information the user might expect. However, there is more to context than location (Schmidt, Beigl, and Gellersen 1999). Relying only on the location sometimes may lead to irrelevant results, as two persons using an LBS at the same location, or even the same person at the same location but within a different context (e.g. time of the day, seasons, with whom), might expect different answers (Grifoni, D'Ulizia, and Ferri 2018). For effectively supporting the user, LBS should provide information and services adapted not only to the user's location, but also her/his other context information (Raper et al. 2007a). In the past years, a lot of research advances have been made to enabling context-awareness in LBS, particularly on the aspects of context acquisition, context representation, and context adaptation (Grifoni, D'Ulizia, and Ferri 2018; Yurur et al. 2016).

Various studies have attempted to identify the different kinds of context factors that are potentially relevant to an LBS user, and proposed some classifications of context factors (Tiina and Nivala 2005; Hervás, Bravo, and Fontecha 2010). An example (see Figure 2) of a classification of context factors consists of users (e.g. their user profiles, preferences, and emotion status), location, time (e.g. time of the day and seasons), orientation/heading, navigation history, purpose of use, social aspects, physical surrounding (e.g. weather, light, and noise level), and technical aspects (e.g. device and network connectivity) (Tiina and Nivala 2005). This kind of classifications provides some structure for the potential list of context factors, while which factors to be considered and modelled depends on the specific LBS applications. Different methods have been proposed to help LBS developers identify relevant context factors (Huang and Gartner 2012; Kessler 2010). The acquisition of context information can be done using various sources (Grifoni, D'Ulizia, and Ferri 2018), such as sensors that are available on smartphones (e.g. GPS, accelerometer, and gyroscope), wearable sensors (e.g. physiological sensors, such as the ones for sensing emotion and heart rate), or sensors present in the environment (static sensors), as well as monitoring or querying Web applications and services or obtained from users' explicit inputs when using the application. Several studies focus on deriving high-level context information (e.g. 'driving') from low-level raw data, especially numeric sensor outputs (Yurur et al. 2016).

The collected contextual data need to be represented through a context model to allow efficient structuring and retrieval of these data (Strang and Linnhoff-Popien 2004). Bettini et al. (2010) identify five context model categories: key-value, markup-based, object-role-based, spatial, and ontology based. Grifoni, D'Ulizia, and Ferri (2018) surveyed many LBS applications and found that the key-value model and the ontology-based model are the most used ones. They further proposed a set of requirements that ensure good performance of the context model: mobility, heterogeneity, relationships and dependencies, timeliness, reasoning, scalability, privacy, and human collaboration.

Several studies have investigated how context data can be utilised to adapt services for the user (Grifoni, D'Ulizia, and Ferri 2018; Mokbel et al. 2011). Grifoni, D'Ulizia, and Ferri

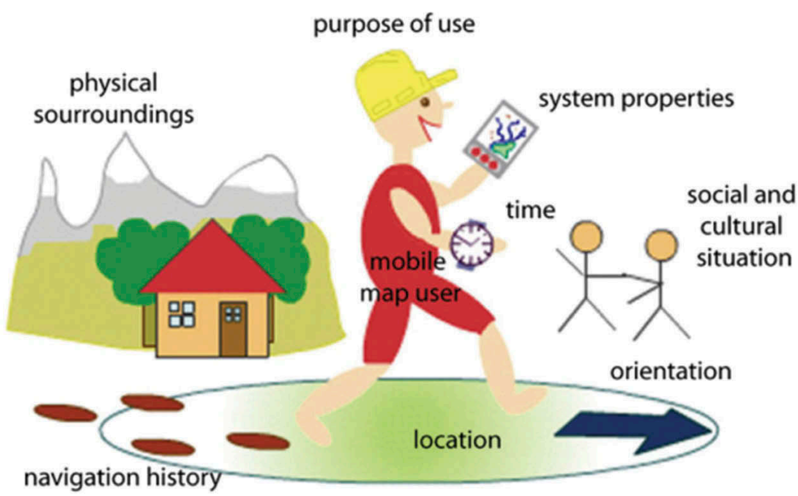

Figure 2. Different types of context factors that might be relevant to LBS (Source: steiniger, neun, and edwardes (2006) at cartouche http://www.e-cartouche.ch/, under CC BY 2.0).

(2018) categorised techniques used in context-aware adaptation into four types: similarity-based reasoning (Guessoum, Miraoui, and Tadj 2015), collaborative filtering (Huang 2016), machine learning, and rule-based reasoning (Raubal and Panov 2009). These different techniques vary in the flexibility they allow, as well as the adaptation quality (e.g. precision and recall) they offer. In terms of the automation of the adaptation process, Schou (2008) differentiates between self-adaptation (the system adapts without any interaction with the user) and controlled adaptation (the user needs to initiate the process). Huang and Gao (2018) argue that adaptive services (self-adaptation) rather than adaptable ones (controlled adaptation) should be introduced for LBS applications, considering the fact that LBS users are often involved in many tasks and activities while using mobile devices. Additionally, the small screen sizes restrict interaction functionalities on these mobile devices.

These rapid advances in context acquisition, representation and adaptation have triggered many context-aware LBS, such as for navigation and wayfinding (Raubal and Panov 2009), location recommendations and mobile guides (Huang 2016), mobile learning (i.e. learning experiences delivered via mobile devices) (Gómez et al. 2014), healthcare (Ham, Dirin, and Laine 2017), and entertainment (Lee et al. 2017).

2.4. *Towards non-intrusive user interfaces*

As shown in Raper et al. (2007b), early LBS applications mainly communicated information to the users via visual (e.g. maps) and auditory (e.g. verbal instructions) interfaces on smartphones. Recent years have seen rapid advances towards more 'natural' and non-intrusive user interfaces for LBS, particularly on the aspects of representation forms (e.g. visual, auditory, and tactile), interface technologies and devices (e.g. smartphones and smartwatches), interaction modality (e.g. touch, gesture, and gaze based), and context awareness.

Visual interfaces, particularly mobile maps, are still the main communication form in LBS (Hirtle and Raubal 2013). However, new types of visual interfaces, such as 3D (Santana et al. 2017), virtual reality (VR), and AR (Huang, Schmidt, and Gartner 2012; Tsai et al. 2017), are being developed. Tactile interfaces, such as vibration on smartphones and wearable sensors, are also used in LBS (Pielot et al. 2011). There is also a trend of combining multiple presentation forms (e.g. maps and voices) to achieve better user experience in LBS. Research attention has also been drawn to compare the effectiveness of different interfaces in LBS (Huang, Schmidt, and Gartner 2012; Gkonos, Giannopoulos, and Raubal 2017). In terms of interface technologies and devices, smartphones are not the only mobile client in LBS. More and more mobile and wearable devices are introduced for LBS applications (Figure 3), such as smartwatches (Wenig et al. 2017), digital glasses (e.g. Google Glasses and Epson Moverio BT-200) (Rehman and Cao 2017), mobile projectors (e.g. smartphones with in-built projector) (Wolf et al. 2016), head-mounted displays (HMDs), haptic devices (Pielot et al. 2011), as well as public displays (Coenen, Wouters, and Moere 2016). In addition to conventional interaction methods, such as touch, voice-based (B. Lee et al. 2015), gesture-based (Rautaray and Agrawal 2015), and gaze-based methods (i.e. use eye movement to control interaction) (Anagnostopoulos et al. 2017) have been introduced for LBS applications as well.

More and more people are carrying different mobile devices (e.g. smartphones, smartwatches, digital glasses, and other wearable sensors) at the same time. Therefore, several studies have started to explore cross-device interaction in LBS (Kubo et al. 2017; Kim et al. 2016). For example, Kubo et al. (2017) explore context-aware cross-device interactions

Figure 3. Emerging interface technologies in LBS.

between a smartphone and a smartwatch. There are studies combining smartphones with other devices in the environment, for example, with digital signage (Ogi, Ito, and Ukegawa 2018) and public displays (Rukzio, Müller, and Hardy 2009).

Another rapid advance can be observed in context-aware user interfaces in LBS (Tiina and Nivala 2005; Raubal and Panov 2009; Griffin et al. 2017). Context information has been used to adapt the contents to be presented, as well as the ways how these contents are presented. For example, Tiina and Nivala (2005) adapt mobile tourist maps to the current season, as well as to the users and usage situations. Raubal and Panov (2009) use location, time (e.g. daytime vs. night-time), velocity, and direction for adapting mobile maps for pedestrian navigation. Anagnostopoulos et al. (2017) propose the concept of gaze-informed LBS, which can provide information according to what a user is looking at. Recently, Griffin et al. (2017) have presented a research agenda in designing context-aware maps, and highlight several key open research questions, such as on modelling of map users and map use context, as well as on the reliability and validity of the context model to make a design transferrable.

2.5. *Usability, privacy, and social aspects of LBS*

In the early 2000s, the LBS research community had mainly focused on the technical challenges, and relatively little attention was paid to non-technical issues (Raper et al. 2007b). Recent years have seen an increasing interest in adopting interdisciplinary research in LBS. Usability evaluation with intended users has become a 'default action' when developing LBS (Meng, Zipf., and Stephan 2007). There is also a body of research focusing on understanding motivations for and acceptance of LBS applications (Yoon, Kim, and Connolly 2017). Beyond usability and user motivation, many studies have started to investigate the social, ethical, and legal aspects brought by LBS (Abbas, Michael, and Michael 2014;

Brimicombe 2012). For example, Abbas, Michael, and Michael (2014, 11) provide a state-of-the-art review, and argue that the two prominent ethical dilemmas in LBS are 'the risk of privacy breaches' and 'the possibility of increased monitoring leading to unwarranted surveillance by institutions and individuals'. Different technical solutions, as well as regulatory considerations/actions have been proposed to tackle these ethical challenges (Kerski 2016). For example, different so-called privacy enhancing methods have been developed to address users' privacy concerns in LBS, such as privacy-by-design, and anonymisation (e.g. spatial cloaking, space transformation, and geomasking) (Duckham, Mokbel, and Nittel 2007; Zhang et al. 2017)， which however does not seem to be widely adopted by companies yet. In terms of regulatory actions, recently a new European Union (EU) law 'General Data Protection Regulation (GDPR)' has come into force, which focuses on data protection and privacy of all individuals within the EU. In addition to these social, ethical, and legal issues, researchers have also explored the business issues in LBS (Dhar and Varshney 2011).

Research interests have also been drawn to study the impact of LBS on both individuals and society in the mobile information era (Raubal 2011). For example, several studies have focused on the impact of LBS on users' spatial awareness, spatial memory, and sense of place, in the context of navigation systems (Huang, Schmidt, and Gartner 2012; Parush, Ahuvia, and Erev 2007), and location based games (Colley et al. 2017). Researchers have also investigated how LBS influence consumers' choice behaviour (Gazley, Hunt, and Lachlan 2015), and the changes to healthier mobility behaviour (Jing, Freeman, and Mu 2016).

As more and more LBS are entering into the general public's daily lives, we expect that research on these aspects will become more prominent, which will enable us to better understand the impact of LBS on our mobile lives and vice versa.

2.6. *Mining big spatial data to better understand our society*

The increasing use of LBS, as well as the growing ubiquity of location/activity sensing technologies have led to an increasing availability of location based tracking data (e.g. floating car data and georeferenced mobile phone data), social media data (e.g. Twitter data), and crowdsourced geographic information (Capineri et al. 2016). These data have created unprecedented opportunities for researchers from various disciplines. Mining these data (e.g. via data mining or visual analytics) enables people to better understand and model human mobility (Shaw, Tsou, and Xinyue 2016; Yuan, Raubal, and Liu 2012), geosocial networks (Scellato et al. 2011), city dynamics, and semantics (Gao, Janowicz, and Couclelis 2017), as well as to monitor and optimise traffic (Keler 2017), detect real-time events, and manage disasters (De Albuquerque et al. 2016). This research is part of an emerging transdisciplinary field named 'urban informatics', which investigates the 'acquisition, integration, and analysis of big and heterogeneous data generated by diverse sources in urban spaces, such as sensors, devices, vehicles, buildings, and humans, to tackle the major issues that cities face (e.g. air pollution, increased energy consumption, and traffic congestion)' (Zheng et al. 2014, 3), and thus improve the quality of life (Ratti and Claudel 2016).

2.7. *Summary and discussion*

As discussed in the above sections, by comparing the state-of-the-art in 2007 as presented in Raper et al. (2007a, 2007b) and the current state, several key trends can be observed from the research and industrial development in the LBS domain over the last 10 years: from mobile guide and navigation systems to more diverse applications, from outdoor environments to indoor and mixed outdoor/indoor environments, from location-awareness to context-awareness, from smartphone-based mobile maps and audio only to more diverse and 'natural' user devices and interfaces, from technology-driven to more holistic research considering both technical and non-technical issues (e.g. social and ethical aspects), as well as the rise of analysis of (big) LBS-generated data. It is important to note that while rapid advances have been made on these aspects, many open issues still exist, especially concerning ubiquitous positioning, context modelling and context-aware LBS, social, ethical and behavioural implications.

As mobile devices and communication technologies seem to continuously be improved at a very fast speed, as well as the increasing smartness of our environments and cities (e.g. with different kinds of sensors), we expect the demand of LBS in different aspects of our daily life will continue to be very strong, which will push LBS towards the 4A vision (anytime, anywhere, for anyone and anything). This will open up a lot of additional research questions, both basic and applied, to the LBS research community in the coming years.

3. Scientific research agenda

To motivate further LBS research and stimulate collective efforts in our rapidly evolving mobile information society, we believe that it is important to develop a cross-cutting research agenda, identifying the key research questions and challenges that are essential to meet the increasing societal demands of LBS. The development of this research agenda was designed as a joint activity of the LBS research community, which mainly consists of experts from GIScience, cartography, geomatics, surveying, computer science, and social sciences. Based on the 31 one-paragraph proposals, and the feedback and results of the workshop and conference session, we identified a list of 'key research challenges' that should be addressed to bring LBS to a higher level to better benefit our human society and environment.

These research challenges can be classified into seven broad areas (Figure 4): Positioning, Modelling, Communication, Evaluation, Applications, Analysis of LBS-generated data, and Social and Behavioural Implications of LBS. The first three areas (the inner groups) represent the core of LBS ('How to make it work'), as every LBS application needs to handle the main tasks of positioning, data modelling, and information communication. 'Evaluation' is important to ensure that a developed LBS meets users' needs. Sufficiently addressing these four aspects would prepare LBS to be ready for different kinds of applications, such as navigation, mobile guides, transportation, healthcare, and entertainment. These LBS applications not only help to facilitate people's daily activities and decision-making in space, but also generate a lot of data about how people use, travel, and interact with each other in the environment. 'Analysis of LBS-generated data' (e.g. location based tracking data, social media data, and crowdsourced geographic information) helps to better understand people's behaviours in different environments, which enables various innovative applications (e.g. transport, urban planning, and smart city), as well as provides insights to further improve these LBS applications. Beyond these, 'social and behavioural implications of LBS' raise as LBS enter into people's daily lives.

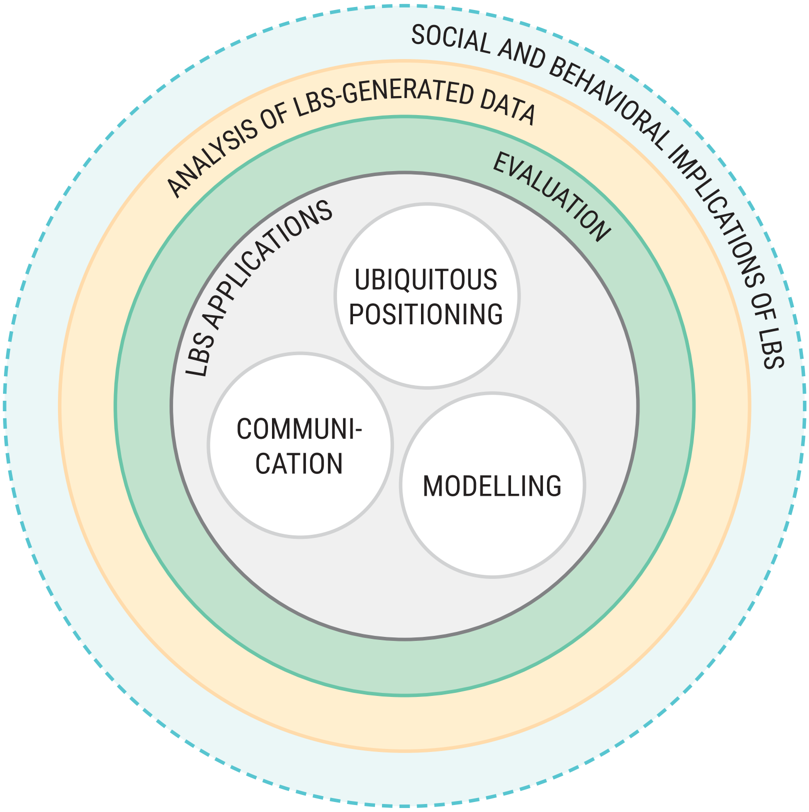

Figure 4. The 'key research challenges' organised into seven broad areas: positioning, modelling, communication, evaluation, applications, analysis of LBS-generated data, social and behavioural implications of LBS.

In the following, we introduce each of these identified research challenges, mainly focusing on their importance, extent, open questions, existing research efforts (if any), and potential opportunities. We don't particularly focus on specific types of LBS 'Applications', as sufficiently addressing the other identified challenges would prepare LBS to be ready for different kinds of applications.

3.1. *Ubiquitous positioning*

To provide services and content relevant to the location, LBS need to determine where the user is. Therefore, positioning or location determination is a crucial technology for LBS (Raper et al. 2007a). As LBS become increasingly important and pervasive in our daily life, ubiquitous positioning is needed to provide an accurate and timely estimate of a user's or an object's location at all times and in all environments (Chen 2012). While GPS (as well as some other similar systems, such as GLONASS, Galileo, and BeiDou) is available in outdoor environments, its positioning accuracy varies, and often gets worse in dense urban environments (due to urban canyon effects). For indoor environments, while other positioning methods and technologies start to appear, such as WiFi-based fingerprinting and Bluetooth beacons, achieving accurate and reliable positioning is still a long way to go. In this section, we present challenges that refer to these issues in the context of LBS.

3.1.1. *Challenge 1.1: How can we determine an object's position in indoor environments and other adverse GNSS conditions? Can sensor fusion help?*

In many cases in outdoor environments, Global Navigation Satellite Systems (GNSS), such as GPS have made location determination a trivial problem. In others, such as indoors, dense urban environments and the underground, accurate positioning nowadays is still a considerable technical challenge, despite the recent advances in indoor positioning. This is due to many reasons caused by the complexity of the environments, such as blockage of signals, severe multipath, etc. The current proposed positioning methods have specific advantages and disadvantages. A stringent requirement is that high performance must be achieved using low-cost technologies and sensors. Thus, smart hybrid positioning where different absolute and relative location technologies are integrated is a major research topic. In this context, main challenges are the development and improvement of existing and emerging positioning technologies and their sensor fusion where more than one type of algorithm at the same time has to be employed.

3.1.2. *Challenge 1.2: How can we 'standardise' the service interface of indoor positioning solutions?*

Currently, different indoor positioning solutions have been proposed, which rely on different sensors, infrastructures, and positioning techniques, and yield different levels of accuracy and reliability. A universal solution, such as GPS for outdoor environments is still missing, and seems unrealistic to estimate a user's or an object's location in indoor environments. This hinders the development of indoor LBS, as users will always need to switch to indoor positioning methods when entering a new indoor environment. If we can 'standardise' the service interface of different indoor positioning solutions (such as GPS for outdoor environments, or OGC's Web Map Service WMS, Web Feature Service WFS, and web processing service WPS, which standardise the input/output of geospatial data and processing services), then an indoor LBS application would work smoothly across different indoor environments despite the different positioning solutions that are deployed. As a step further towards this 'standardisation', research should be done to study what metadata are needed to characterise and specify the service interface of different indoor positioning solutions. Existing standards on geospatial metadata provide some hints on these aspects.

3.1.3. *Challenge 1.3: Can guidelines on the levels of positioning accuracy and reliability required for various LBS application domains be developed?*

The application domains of LBS are continually expanding. To provide useful information, different LBS applications have different location accuracy requirements, particularly in terms of positional accuracy (vertical and horizontal), frequency of access (allowing higher sampling rates), reliability (overall consistency of a measure in different conditions), and latency (e.g. time-to-first-fix). For example, the level of positioning accuracy required for navigation systems is much higher than when providing weather information for a user location. While from the service provider's perspective, more accurate location information is generally more useful, this often results in higher cost and might not be necessary or allowed (e.g. due to the nature of the applications, as well as privacy considerations). This challenges the research community to determine minimum local accuracy requirements for various LBS application domains. Several early studies have investigated GPS sample rates for developing pedestrian assistant systems (e.g. Schneider et al. (2016)) and animal home range analysis in movement ecology (e.g. Kie et al. (2010)), but little research attention has been paid to other aspects and domains mentioned above.

3.2. *Modelling*

For effectively supporting users, LBS should provide information and services relevant to the location, characteristics, needs, and context of a mobile user. These kinds of information about the users and their context are important considerations in the course of designing LBS. They determine what contents should be provided, and have a significant impact on the way systems and user interfaces should be designed. While this issue has attracted significant interest, its research is still at an early stage. Modelling and using these kinds of information to provide personalised and context-aware services in LBS is still challenging.

3.2.1. *Challenge 2.1: How can indoor environments be modelled to effectively support LBS applications?*

To support various queries, the space which the user is in should be effectively modelled for LBS. While spatial modelling of outdoor environments has been standardised to some extent, research on modelling indoor environments for LBS is only emerging. A number of indoor space models have been proposed from different disciplines and perspectives (Afyouni, Ray, and Claramunt 2017), such as cityGML, BIM, and network models, without explicitly addressing the geometrical and semantical requirements introduced by indoor LBS. Compared to other applications (such as architectural or visualisation applications), indoor LBS (e.g. finding the 'LBS 2018 conference' room) often require more semantic than purely geometrical information. Research efforts should be made to evaluate whether the existing models can effectively support different indoor LBS applications, such as indoor wayfinding, emergency evacuation, mobile guide (shopping or exhibition), gaming, and advertisement. The dynamic nature of many indoor environments also poses challenges in modelling the semantics of indoor space. Addressing these aspects requires a better understanding of different indoor LBS applications, as well as the diversity of indoor environments. Research attention should also be paid on combining outdoor and indoor data models to provide mixed outdoor/indoor LBS. Another issue is related to privacy. Indoor environments often consist of personally sensitive places. How to effectively represent indoor environments while preserving privacy is still an open question.

3.2.2. *Challenge 2.2: How can context of a mobile user, as well as its dynamics be modelled in LBS?*

Context is 'any information that can be used to characterise the situation of an entity. An entity is a person, place, object that can be considered relevant to the interaction between a user and an application' (Dey 2001, 5). In this sense, location is part of context, however, there is more to context than location, such as the user (e.g. his/her preferences, skills, cognition, and goals), physical environment (e.g. weather, temperature, surrounding landscape, and events), social aspects (e.g. who is with the user, and social relationships), and technical aspects (e.g. device and network connectivity). Four main questions need to be addressed:

(1) What kinds of context information should be considered and modelled in LBS? While the answer depends on the specific LBS application, *methods* to identify relevant context information to be modelled in a specific LBS application should be developed.
(2) How can context information be acquired and inferred? Different sources are potentially available, such as sensors (smartphone sensors, wearable sensors, sensors in the environment), web applications and services (e.g. online social media), and also users' explicit inputs. This challenges researchers to develop methods to integrate these different sources, as well as to derive high-level context information (e.g. sightseeing) from low-level raw data. Moreover, during this context acquisition process, uncertainty regarding the acquired context should be modelled.
(3) How should the acquired context information be structured and modelled to allow efficient retrieval and update? A main challenge here is the interdependency among different context dimensions. The principles of linked data might play a role here.
(4) How can the dynamics of context be modelled in LBS? LBS are often used in dynamic and mobile environments, which implies that the dynamic nature should be considered when addressing the above three questions. Solutions should also be developed to manage the incoming context data streams.

3.2.3. *Challenge 2.3: How can personalisation and context-aware adaptation be provided in LBS? Which level of automation should the adaptation process have?*

After acquisition and modelling, the context data can be used in LBS to adapt the services and contents for the user. Context-aware adaptation is the process of tailoring the observable behaviour, functionalities, contents and/or the appearance of the service in reaction to a change of the user's context, with the aims to provide a better user experience. While research on this has been emerging in the past years, several key questions still need extensive research efforts, especially concerning the following aspects: (1) What: which features of LBS can be adapted? (2) How: which techniques are needed to make the adaptation? (3) When: when should the adaptation process happen? The dynamics and uncertainty nature of context bring further challenges to these questions.

Another important question is 'which level of automation should the adaptation process have'. While a high level of automation (e.g. self-adaptation) requires no interaction of the user with the system, the user might get a feeling of losing control over the system. This challenges researchers to find a balance between level of automation and level of user interaction.

The context data that are used in the adaptation process often consist of the user's personal information or travel histories, which may raise privacy concerns. The more available the context data is, the better services the user will receive. There is a trade-off between the quality of the adaptation and the amount of private sensing data. Further efforts are necessary to find a balance between these aspects.

3.2.4. *Challenge 2.4: How can LBS be designed to support collective actions, tasks, and activities (LBS for group users)?*

Currently, LBS are mostly developed to facilitate single users' activities and decision-making in space. In the real world, many of our activities and decision-making processes involve other individuals. We might navigate in an unfamiliar environment with friends to find a particular destination, explore a city or museum together, or plan a meeting place while each individual is on the move. It is still rather unclear how LBS should be designed to support this kind of collective actions, tasks, and activities. While research on location based social networks, location based gaming and mobile crowdsourcing has generated some insights on this, there are still many types of group-based interactions to be considered for LBS, regarding whether the users are together or distributed at different places (same place vs. different places), whether the interaction happens synchronously or asynchronously (same time/real-time vs. different time), and how many mobile devices are used (one shared device vs. one device per user). Designing LBS to support collective tasks and activities also needs to consider all involved users' preferences, needs and context, and develop mechanisms to resolve conflicts and enable collaboration. Methods on preserving privacy in this kind of applications also need to be developed.

3.3. *Communication (interface and interaction)*

From a user's perspective, LBS provide relevant information via mobile devices to support their decision-making and activities in space. This can be considered as a communication process, in which relevant (spatio-temporal) information is conveyed from LBS to the users. While much research progress has been made regarding this aspect, significant attention should still be paid to develop more 'natural' and non-intrusive user interfaces for LBS.

3.3.1. *Challenge 3.1: How can relevant information be communicated to LBS users in an optimal way to facilitate their decision-making and activities in space?*

Maps are generally considered as the most important presentation form when communicating georeferenced information. This also seems to hold for LBS, as many of the questions LBS try to answer are geo-related. In addition to maps, other communication forms, such as speech and text are also employed in LBS. While early research efforts in LBS focused on designing maps adapting to small screens of mobile devices and specific user tasks (e.g. wayfinding) (Dillemuth 2008), there are more aspects to consider, especially regarding the diversity of LBS users, tasks, and use contexts. In other words, context-aware adaptation should be introduced when communicating information in LBS. To achieve this, several essential issues should be addressed. First, a systematic framework to study users and their contexts, as well as their information needs should be developed. Second, techniques to provide context-aware interfaces in LBS to effectively communicate information (e.g. via maps or other communication forms) are needed. For this, it is important to understand 'which contents and presentation styles are relevant for which communication goals and which contexts' (Huang 2015, 2). Answering these questions will need empirical studies with computational methods.

3.3.2. *Challenge 3.2: How can we employ newly emerging mobile devices (e.g. smart watches and smart glasses) for LBS applications?*

Recent years have seen a range of new interface technologies and devices being introduced for communication of spatial information in LBS (Oviatt et al. 2017), such as wearable devices like smartwatches and digital glasses, and haptic devices. These kinds of devices often have their own characteristics, interaction modalities (e.g. voice, gesture, and gaze-based interaction), and technical constraints. To make use of these new technologies, conventional interface design principles, techniques, rules and their relative priority should be improved, updated and even re-defined if needed. Moreover, development in interface technologies and mobile devices is continually at a fast speed. This will challenge researchers from the LBS domain and other domains, such as mobile human-computer interaction (HCI) to explore what design patterns/principles are still valid, and work for future emerging devices.

3.3.3. *Challenge 3.3: How can visual, sound, and tactile methods be meaningfully integrated to effectively communicate spatial information in LBS?*

While maps seem to be a very popular communication form in LBS, recent research attention has also been paid to explore the possibilities of using other human senses, e.g. hearing and touch (haptic). Furthermore, new forms of visualisation beyond maps, such as 3D, VR, and augmented reality, are being developed. However, a systematic understanding of strengths and weaknesses of these visual, auditory, and tactile forms, as well as when they might be suitable to apply is still missing. Since they all have strengths and weaknesses, it is also essential to study which and how they can be meaningfully integrated to communicate (spatial) information in LBS.

3.4. *Evaluation methodology*

While research has contributed to enabling LBS and keeps pushing the limits of LBS, the evaluation of such services regarding usability and usefulness is still not well understood. The lack of understanding in this particular area of LBS has a significant impact on the development of the field as a whole. For example, in order to ensure reliable progress (both in research and in practice), evaluation methods are required that facilitate comparison of different services and approaches.

3.4.1. *Challenge 4.1: How can a comprehensive framework for evaluating LBS applications be developed, considering user interfaces, user properties and skills, cognition, device and service properties, environmental factors, and social aspects?*

As mentioned before, evaluation is important to ensure that a developed LBS meets users' needs, and it is also essential for the further development of the field as a whole. There is a strong need to systematically investigate test environments (Li and Longley 2006) and evaluation methods for LBS: properties of existing environments and methods must be assessed, and new test environments and methods (e.g. mobile eye tracking) explored. In order to further improve the usefulness and acceptance of LBS, it is essential to thoroughly evaluate them and to determine which method and environment to use when (Delikostidis et al. 2015). Due to the complex nature of LBS and their strong dependency on contextual factors, there is also a clear need to investigate how to best combine methods when evaluating different types of LBS. One of the key challenges in this context relates to the fact that LBS are often used while people are on the move, and therefore dynamic aspects of mobile decision-making must be considered (Hirtle and Raubal 2013). While usability is still one of the main concerns for the evaluation of mobile applications (Harrison, Flood, and Duce 2013), a comprehensive framework for LBS evaluation must also account explicitly for the following characteristics: user interface, user properties and skills, cognition, device and service properties, environmental factors, and social aspects.

Such a comprehensive framework for evaluating LBS applications must systematically investigate all components and relationships within the User – Technology – Environment triangle. User issues relate not only to the usability and user experience (Paay and Kjeldskov 2008) of the particular LBS applications, but also to their potential adaptation to user context (Raubal and Panov 2009), optimal ways of communicating information to the user, and taking into account aspects of spatial cognition (Montello and Raubal 2013), learning, and behaviour change (Bucher et al. 2016). A user-centric model, as proposed in (Richter, Dara-Abrams, and Raubal 2010), supports the evaluation of these aspects by distinguishing different degrees of user involvement and highlighting the effects that differences in interaction have for the users. When evaluating LBS technology, one must take into account the often complex computing architectures that LBS are embedded in, including multiple servers and clients, running on different platforms, and having different performance issues. For the evaluation it is mandatory to first specify the various requirements, which must be met by the LBS. Such requirements relate to system performance, scalability, and device properties. In addition, security and privacy (Bettini, Mascetti, and Sean Wang 2008) must be taken into account. Environmental context plays a large role when evaluating LBS applications. Questions, such as 'which environmental factors impact the use of LBS and how' must be asked. Such factors could be complexity of the environment (indoors and outdoors), weather, crowdedness, or air quality. In addition, the relation between the movement of the user (self-propelled or via a means of transportation) and the use of LBS needs to be considered explicitly.

3.4.2. *Challenge 4.2: How can lab-based and field-based evaluation be effectively combined in LBS research?*

LBS evaluation can be performed in the lab or in the field. Lab studies have the advantage of being under controlled conditions and being done faster and cheaper than studies in real world environments. This comes at the price of losing ecological validity because the real environments where LBS applications will eventually be employed, are more complex, dynamic, and unpredictable. Researchers have also argued that people behave differently in the lab compared to the real world (Kaikkonen et al. 2008). More research needs to be done to investigate the strengths and weaknesses of employing lab-based and field-based methods in evaluating LBS, as well as how to best combine them.

Furthermore, through advancements in areas, such as VR, it is nowadays possible to utilise hybrid approaches, which bridge the gap between lab and real world studies. There are several initial studies heading into this direction. For example, Delikostidis et al. (2015) used an Immersive Video Environment to evaluate mobile navigation systems and demonstrated that nearly the same number of major usability problems could be identified as in a field test. However, a systematic understanding of the potentials and limitations of virtual environments for LBS research is still missing.

3.5. *Analysis of LBS-generated data (e.g. tracking data and social media data)*

The increasing ubiquity of LBS and location sensing devices have led to a huge amount of data, such as location based tracking data, social media data and crowdsourced geographic information. On the one hand, these data can be used to better understand LBS users and their contexts, which can be used to further improve LBS applications. On the other hand, these data provide insights on how people move and behave in different environments and socialise with others. Therefore, analysis of these kinds of LBS-generated data has attracted significant interest from different fields and disciplines.

3.5.1. *Challenge 5.1: Data models of LBS-generated data*

To support efficient data analysis and knowledge discovery, LBS-generated data should be modelled and stored appropriately. The classic geospatial data representation models may not be able to capture all important aspects of the large volume of enriched LBS-generated data and relationships among them. Currently, lots of LBS-generated data are still simply modelled and stored in relational databases and even comma-separated values (CSV) files, which leaves the complexity to the data analysis process, and makes it difficult to scale up when the data amount increases significantly. Compared to conventional geospatial data, LBS-generated data often show most (if not all) of the typical characteristics of big data: volume, variety, velocity, and veracity.[2] A key question here is: How can we represent and store LBS-generated data to allow efficient retrieval (and update), considering the characteristics of the data? A unique data model for all kinds of LBS-generated data might not be feasible, and therefore, as a first step, it would make sense to identify the types of these data (e.g. sensor data vs. human reported data vs. hybrid one), and develop data models for each of these different types. One of the essential requirements of these kinds of data models are their abilities to support further integration of other data sources, as recent years have seen that more and more data sources are available for a single phenomenon, event, or area. Metadata regarding the quality and other characteristics (e.g. representativeness) of the data should also be considered and modelled together with the data. Furthermore, as LBS-generated data often consist of user's personal information or travel histories, methods to deal with privacy during modelling and storing these data should be developed.

3.5.2. *Challenge 5.2: Analysis of LBS-generated data*

The increasing amount and complexity of LBS-generated data has also imposed tremendous challenges on the approaches to the analysis and use of them. Analysis of these data has attracted various research interests in the domains of Knowledge Discovery and Data Mining (KDD) and visual analytics. Li et al. (2016) and Robinson et al. (2017) provide research agendas from geospatial perspectives, and identify a list of key research questions related to the different aspects of geospatial big data. In addition to the research questions they identified, several further questions should be highlighted, especially for LBS-generated data. First, as LBS-generated data often contain some personal information (e.g. travel histories) of the users, there is a strong need to develop privacy-preserving analytical approaches for processing these data. Second, as mentioned before, more and more LBS-generated data, as well as other data are generated which potentially offer different perspectives for a same study area, phenomenon, and event. It is therefore necessary to develop analytical approaches which can integrate these different data sources to offer a more comprehensive picture of the phenomenon. Third, analytical approaches should also be developed to consider the quality (e.g. representativeness, bias, and uncertainty) of the data, and model the impact of these quality issues on the analysis results. For example, one of the most intensively studied LBS-generated data is location based social media data (e.g. data from Twitter and Flickr), which have issues related to how representative their contributors are as well as some other systematic and non-systematic biases (Olteanu et al. 2016). Modelling these biases in the analysis process would allow to better interpret the results, as well as to generalise the findings to a larger extent.

3.6. *Social and behavioural implications of LBS*

Privacy issues have been a long-standing challenge for LBS. In recent years, the increasing use of LBS, as well as the growing ubiquity of location/activity sensing technologies in our daily life are significantly changing the way people interact with each other and their behaviour in different environments. They also bring further privacy challenges, as well as some other social, legal, ethical issues.

3.6.1. *Challenge 6.1: How do LBS influence people's spatial abilities? How can we design LBS that facilitate people's activities and decision-making without harming their spatial abilities?*

While LBS (e.g. navigation systems) can facilitate people's daily activities and decision-making, they potentially bring some side effects. As mentioned by Montello Daniel (2009, 1835), 'technologies change how we think, often by reducing our ability to reason effectively without the technology'. Therefore, there is a strong need to understand the potential side effects of over-reliance on LBS in our daily life. Several initial studies have started to investigate these issues, and found that over-reliance on navigation systems actually harms our spatial knowledge acquisition and spatial ability (Huang, Schmidt, and Gartner 2012; Parush, Ahuvia, and Erev 2007). However, until now, a systematic understanding of these issues and their relationship to other individual differences is still missing, and very challenging, as it requires longitudinal empirical research (Griffin et al. 2017). Furthermore, as these potential side effects seem to exist, it is important to direct research to explore how LBS can be designed to facilitate people's activities and decision-making without harming their spatial abilities.

3.6.2. *Challenge 6.2: How do LBS influence the way people interact with each other and their behaviours in different environments?*

With the rapid advances in mobile information technologies, LBS are entering into the general public's daily life. Recent years have seen an increasing number of people using LBS to facilitate their daily activities and decision-making, such as finding their ways in unfamiliar environments, exploring a new city, networking with friends, and entertaining. As LBS and more broadly mobile information technologies have become an integral part of our daily life, it is necessary to study their impact on both individuals and our society, particularly on how these technologies influence the way we interact and socialise with each other, and our behaviours in different environments. Research on this aspect would also require interdisciplinary and longitudinal efforts.

3.6.3. *Challenge 6.3: What are privacy and ethical issues in LBS? How can we best address users' privacy and ethical concerns in LBS? How do LBS influence/change our understanding of privacy and ethics, as well as our responses to them?*

LBS in nature provide relevant information to users by making use of their current location and preferences, as well as the context they are in. This information might be private and thus very sensitive, and therefore, often raises privacy concerns. In connection to this, 'the possibility of increased monitoring leading to unwarranted surveillance by institutions and individuals' (Abbas, Michael, and Michael 2014, 11) has led to many social and ethical issues beyond purely privacy. While research on privacy and LBS has been emerging in recent years and several technical solutions have been proposed, significant research attention should still be paid to the following questions: 'what are privacy and ethical issues in LBS?', and more importantly, 'how can we best address users' privacy and ethical concerns while ensuring the service quality of LBS?'. Answering these questions requires research efforts from both technical and non-technical (e.g. regulatory considerations) perspectives. What makes them even more challenging is that concern about privacy and ethical issues seems to be perceived differently in different cultures, in different countries, by different people, and in different contexts.

Another important aspect is that while LBS raise many privacy and ethical concerns, they also influence/change our understanding of privacy and ethics, as well as our responses towards them. It is therefore necessary to gain a better understanding of this aspect.

3.6.4. *Challenge 6.4: What are the business models of LBS?*

Recent years have seen that LBS and location tracking technologies are becoming disruptive and transformative, as they are bringing radical changes to many business and social sectors, such as healthcare and well-being, finance (e.g. vehicle insurance), transportation, advertisement, and public administration. While LBS have been gaining significant commercial interests, there are still few substantial studies on LBS business models. Furthermore, it is also important to understand the impacts of LBS on these business sectors, and how these sectors provide further inputs for advancing the development of LBS.

4. Towards location based science (LBscience)?

While the early development of LBS seems to be mainly driven by applications and technology, researchers in the LBS community actually have been trying to focus on the foundational research issues that are independent of applications and technology. As an example, the above research agenda aims to contribute an updated perspective on the future of LBS research. To motivate further research, it might be necessary to recognise and develop the role of science in LBS.

In general, the scientific domain that many LBS researchers have been working on, as well as the above research agenda aims to contribute to can be defined as a field that studies computational techniques, and social and ethical issues of deriving, modelling, communicating, and analysing of location based information, i.e. information relevant to users' or intelligent agents' locations. It concerns scientific knowledge on which LBS applications are based. Firstly, it considers both computational techniques that enable the implementation of LBS applications, and social and ethical issues that rise as LBS applications enter into everyday life. Secondly, it deals with deriving, modelling, communicating, and analysing of location based information, in which 'deriving' is based on ubiquitous positioning and context acquisition, 'modelling' concerns computationally representing location based information, 'communicating' is about conveying location-based information to a user or intelligent agent, 'analysing' focuses on the analysis of LBS-generated data. All above issues are inline with the research agenda outlined in Section 3.

This raises a series of interesting and important questions: Can we call this scientific domain Location Based Science (LBScience)? In other words, is there a LBScience for LBS, like Geographic Information Science (GIScience) (Michael F. Goodchild 1992; 2010) for geographic information systems (GIS)? If yes, what is its study subject? What are the generic (rather than specific to particular fields of applications or particular technologies) questions that make up LBScience? What are the boundaries of LBScience and its cognate scientific disciplines, such as GIScience?

This paper does not aim to answer these questions, but rather encourages the LBS community to think about them. We believe that by thinking about science rather than software systems, and by identifying the key scientific questions of the field, we can better ensure a long-term prosperous future of the LBS domain.

5. Conclusions

In this article, we first reviewed the state-of-the-art in LBS research, and identified several research trends in recent years. These range from mobile guides and navigation systems to more diverse applications, from outdoor to indoor and mixed outdoor/indoor environments, from location based to context-aware, from maps and audio to more diverse and 'natural' interfaces, from technology-oriented to interdisciplinary research, and analysis of big spatial data. We then presented a series of key research challenges that are essential for further development of LBS (Table 1), setting a research agenda for LBS to 'positively' shape the future of our mobile information society. These research challenges cover issues related to the core of LBS development (e.g. positioning, modelling, and communication), evaluation, and analysis of LBS-generated data, as well as social, ethical and behavioural issues that rise as LBS enter into people's daily lives.

As can be seen in Table 1, many of these challenges often include interdisciplinary characteristics. Therefore, more cross-disciplinary endeavours are anticipated in the future particularly at the intersection of geospatial science (e.g. GIScience, cartography, and geodesy), information and communication technology (ICT, e.g. ubiquitous computing, HCI, and data science), and the social sciences.

While we believe that the research agenda presented in this paper covers the most essential and fundamental open questions that are needed to bring LBS to a higher level, it should be noted that this list of challenges is not meant to be exclusive. Meanwhile, it should also be realised that the content of the research agenda represents a snapshot in time, and will change over time with the new technological and methodological developments, such as those relating to autonomous cars and artificial intelligence. Two general research questions on this aspect: How will LBS look like in the era

Table 1. Research challenges in LBS.

	Research challenges in Location Based Services
Ubiquitous Positioning	• How can we determine an object's position in indoor environments and adverse GNSS conditions? Can sensor fusion help? • How can we 'standardise' the service interface of indoor positioning solutions? • Can guidelines on the levels of positioning accuracy and reliability required for various LBS application domains be developed?
Modelling	• How can indoor environments be modelled to support effective LBS applications? • How can context of a mobile user, as well as its dynamics be modelled in LBS? • How can personalisation and context-aware adaptation be provided in LBS? Which level of automation should the adaptation process have? • How can LBS be designed to support collective actions, tasks, and activities (LBS for group users)?
Communication	• How can relevant information be communicated to LBS users in an optimal way to facilitate their decision-making and activities in space? • How can we employ newly emerging mobile devices (e.g. smart watches, smart glasses) for LBS applications? • How can visual, sound, and tactile methods be meaningfully integrated to effectively communicate spatial information in LBS?
Evaluation	• How can a comprehensive framework for evaluating LBS applications be developed, considering UI, user properties and skills, cognition, device and service properties, environmental factors, and social aspects? • How can lab-based and field-based evaluation be effectively combined in LBS research?
Analysis of LBS-generated data	• Data models of LBS-generated data • Analysis of LBS-generated data
Social and behavioural implications of LBS	• How do LBS influence people's spatial abilities? How can we design LBS that facilitate people's activities and decision-making without harming their spatial abilities? • How do LBS influence the way people interact with each other and their behaviours in different environments? • What are privacy and ethical issues in LBS? How can we best address users' privacy and ethical concerns in LBS? How do LBS influence/change our understanding of privacy and ethics, as well as our responses to them? • What are the business models of LBS?

of autonomous cars and artificial intelligence? What are their enabling scientific basis and technologies?

Through our work in the ICA Commission on LBS (http://lbs.icaci.org/) and the Journal of LBS (http://www.tandfonline.com/tlbs20), we hope to organise future activities (conferences, workshops, and special issues) that can bring together the broader community in answering these open research questions and shaping the future of our mobile information society in which LBS play a major role. It is only through collaboration and cooperation within our community and across cognate communities that we will achieve these goals.

Notes

1. Selective availability was an intentional degradation of public GPS signals implemented by the U.S. Govenment for national security reasons.
2. https://en.wikipedia.org/wiki/Big_data.

Acknowledgments

We like to thank the following researchers who contributed one-paragraph proposals of "big research questions in LBS" (https://lbs.icaci.org/research-agenda/): Klemen Kozmus, Domokos Esztergár-Kiss, Eko Sediyono, Kai-Florian Richter, Dirk Wenig, Christian Kray, Peter Kiefer, Max Pfeiffer, Ioannis Giannopoulos, Matthias Seuter, Champika Manel, Sebastian Feld, Martin Werner, Pavel Andreevich Samsonov, Johannes Schöning, Jürgen Döllner, Jochen Wendel, Rui Li, Huanfa Chen, William Mackaness, M.R. Malek, Catia Real Ehrlich, Jörg Blankenbach, Bonan Wei, Jochen Schiewe, Liqiu Meng, Min Lu, H. Sebnem Duzgun, David Jonietz, Dominik Bucher, Stefano De Sabbata, Andrei Popleteev, Thomas Liebig, Peng Jia, Johannes Scholz, Nina Polous, Guenther Retscher, and Konstantinos Papangelis. Additionally, we also appreciate the comments and feedback provided by participants of the "Research Agenda" workshops at LBS 2016 and ICC 2017, particularly: Johannes Schöning, Pavel Samsonov, Mohammad Reza Malek, Dominik Bucher, Sebastian Feld, Guenther Retscher, Rui Li, Edward Verbree, Karl Rehrl, Aleksander Ozga, Győző Gidofalvi, Pia Bereuter, Karel Staněk, Conrad Franke, Lucas Godfrey, Liqiu Meng, Dariusz Gotlib, William Mackaness, Bo Zhao, GenGen He, David Fairbairn, and Keith Clarke. We also thank the editor and two anonymous reviewers for their constructive comments.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Haosheng Huang http://orcid.org/0000-0001-8399-3607
Georg Gartner http://orcid.org/0000-0003-2002-5339
Nico Van de Weghe http://orcid.org/0000-0002-5327-4000

References

Abbas, R., K. Michael, and M. G. Michael. 2014. "The Regulatory Considerations and Ethical Dilemmas of Location-Based Services (LBS): A Literature Review." *Information Technology & People* 27 (1): 2–20. doi:10.1108/ITP-12-2012-0156.

Adibi, S., ed. 2015. *Mobile Health. Vol. 5. Springer Series in Bio-/Neuroinformatics*. Cham: Springer International Publishing. doi:10.1007/978-3-319-12817-7.

Afyouni, I., C. Ray, and C. Claramunt. 2017. "Representation: Indoor Spaces." In *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, edited by D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu, and R. A. Marston, 1–12. Hoboken, NJ: John Wiley & Sons. doi:10.1002/9781118786352.wbieg0900.

Alarifi, A., A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. A. Al-Ammar, and H. S. Al-Khalifa. 2016. "Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances." *Sensors* 16 (5): 707. doi:10.3390/s16122100.

Åman, P., L. A. Liikkanen, and A. Hinkka. 2015. "Enriching User Experiences with Location-Sensitive Music Services." *Journal of Location Based Services* 9 (3): 167–186. doi:10.1080/17489725.2015.1098737.

Anagnostopoulos, V., M. Havlena, P. Kiefer, I. Giannopoulos, K. Schindler, and M. Raubal. 2017. "Gaze-Informed Location-Based Services." *International Journal of Geographical Information Science* 31 (9): 1770–1797. doi:10.1080/13658816.2017.1334896.

Atefeh, F., and W. Khreich. 2015. "A Survey of Techniques for Event Detection in Twitter." *Computational Intelligence* 31 (1): 133–164. doi:10.1111/coin.v31.1.

Bai, Y. 2016. "Development of a WiFi and RFID Based Indoor Location and Mobility Tracking System." Ph.D. thesis, Melbourne: RMIT University.

Bao, J., Y. Zheng, D. Wilkie, and M. Mokbel. 2015. “Recommendations in Location-Based Social Networks: A Survey.” *GeoInformatica* 19 (3): 525–565. doi:10.1007/s10707-014-0220-8.

Bettini, C., O. Brdiczka, K. Henricksen, J. Indulska, D. Nicklas, A. Ranganathan, and D. Riboni. 2010. “A Survey of Context Modelling and Reasoning Techniques.” *Pervasive and Mobile Computing* 6 (2): 161–180. doi:10.1016/j.pmcj.2009.06.002.

Bettini, C., S. Mascetti, and X. Sean Wang. 2008. “Privacy Threats in Location-Based Services.” In *Encyclopedia of GIS*, edited by S. Shekhar and H. Xiong, 906–912. Boston, MA: Springer. doi:10.1007/978-0-387-35973-1_1022.

Brimicombe, A. 2012. “Did GIS Start a Crime Wave? SatNav Theft and Its Implications for Geo-Information Engineering.” *The Professional Geographer* 64 (3): 430–445. doi:10.1080/00330124.2011.609778.

Brimicombe, A., and L. Chao. 2009. *Location-Based Services and Geo-Information Engineering*. West Sussex, UK: John Wiley & Sons.

Bucher, D., D. Jonietz, and M. Raubal. 2017. “A Heuristic for Multi-Modal Route Planning.” In *Progress in Location-Based Services 2016*, edited by G. Gartner and H. Huang, 211–229. Cham: Springer. doi:10.1007/978-3-319-47289-8_11.

Bucher, D., F. Cellina, F. Mangili, M. Raubal, R. Rudel, A. E. Rizzoli, and O. Elabed. 2016. “Exploiting Fitness Apps for Sustainable Mobility – Challenges Deploying the GoEco! App.” In *ICT4S 2016,* edited by P. Grosso, P. Lag and A. Osseyran. The Netherlands: Amsterdam.

Capineri, C., M. Haklay, H. Huang, V. Antoniou, J. Kettunen, F. Ostermann, and R. Purves, eds. 2016. *European Handbook of Crowdsourced Geographic Information*. London, UK: Ubiquity Press. doi:10.5334/bax.

Chen, R., ed. 2012. *Ubiquitous Positioning and Mobile Location-Based Services in Smart Phones*. Hershey, PA: IGI Global.

Choy, S., J. Handmer, J. Whittaker, Y. Shinohara, T. Hatori, and N. Kohtake. 2016. “Application of Satellite Navigation System for Emergency Warning and Alerting.” *Computers, Environment and Urban Systems* 58: 12–18. doi:10.1016/j.compenvurbsys.2016.03.003.

Coenen, J., N. Wouters, and A. V. Moere. 2016. “Synchronized Wayfinding on Multiple Consecutively Situated Public Displays.” *In PerDis’16* 182–196. doi:10.1145/2914920.2929906.

Colley, A., J. Thebault-Spieker, A. Y. Lin, D. Degraen, B. Fischman, J. Häkkilä, K. Kuehl, et al. 2017. ““The Geography of PokéMon GO.” *Beneficial and Problematic Effects on Places and Movement.” In CHI* 2017: 1179–1192. doi:10.1145/3025453.3025495.

Davidson, P., and R. Piche. 2017. “A Survey of Selected Indoor Positioning Methods for Smartphones.” *IEEE Communications Surveys & Tutorials* 19 (2): 1347–1370. doi:10.1109/COMST.2016.2637663.

De Albuquerque, J. P., M. Eckle, B. Herfort, and A. Zipf. 2016. “Crowdsourcing Geographic Information for Disaster Management and Improving Urban Resilience: An Overview of Recent Developments and Lessons Learned.” In *European Handbook of Crowdsourced Geographic Information*, edited by C. Capineri, M. Haklay, H. Huang, V. Antoniou, J. Kettunen, F. Ostermann, and R. Purves, 309–321. London: Ubiquity Press. doi:10.5334/bax.w.

Delikostidis, I., H. Fritze, T. Fechner, and C. Kray. 2015. “Bridging the Gap between Field- and Lab-Based User Studies for Location-Based Services.” In *Progress in Location-Based Services 2014*, edited by G. Gartner and H. Huang, 257–271. Cham: Springer. doi:10.1007/978-3-319-11879-6_18.

Dey, A. K. 2001. “Understanding and Using Context.” *Personal and Ubiquitous Computing* 5 (February): 4–7. doi:10.1007/s007790170019.

Dhar, S., and U. Varshney. 2011. “Challenges and Business Models for Mobile Location-Based Services and Advertising.” *Communications of the ACM* 54 (5): 121. doi:10.1145/1941487.

Dillemuth, J. 2008. “Map Use and Spatial Knowledge Acquisition with Small, Mobile Map Displays.” PhD Thesis, University of California, Santa Barbara.

Duckham, M., M. Mokbel, and S. Nittel. 2007. “Special Issue on Privacy Aware and Location-Based Mobile Services.” *Journal of Location Based Services* 1 (3): 161–164. doi:10.1080/17489720802089489.

Eduardo, P. J., M. Arrue, M. Kobayashi, H. Takagi, and C. Asakawa. 2017. “Assessment of Semantic Taxonomies for Blind Indoor Navigation Based on a Shopping Center Use Case. ”In *W4A ’17*, edited by C. Bailey and V. Gkatzidou. New York, NY: ACM. doi:10.1145/3058555.3058575.

Espeter, M., and M. Raubal. 2009. "Location-Based Decision Support for User Groups." *Journal of Location Based Services* 3 (3): 165–187. doi:10.1080/17489720903339668.
Fellner, I., H. Huang, and G. Gartner. 2017. "'Turn Left after the WC, and Use the Lift to Go to the 2nd Floor'—Generation of Landmark-Based Route Instructions for Indoor Navigation." *ISPRS International Journal of Geo-Information* 6 (6): 183. doi:10.3390/ijgi6060183.
Gao, S., K. Janowicz, and H. Couclelis. 2017. "Extracting Urban Functional Regions from Points of Interest and Human Activities on Location-Based Social Networks." *Transactions in GIS* 21 (3): 446–467. doi:10.1111/tgis.2017.21.issue-3.
Gazley, A., A. Hunt, and M. Lachlan. 2015. "The Effects of Location-Based-Services on Consumer Purchase Intention at Point of Purchase." *European Journal of Marketing* 49 (9/10): 1686–1708. doi:10.1108/EJM-01-2014-0012.
Gkonos, C., I. Giannopoulos, and M. Raubal. 2017. "Maps, Vibration or Gaze? Comparison of Novel Navigation Assistance in Indoor and Outdoor Environments." *Journal of Location Based Services* 1–21. doi:10.1080/17489725.2017.1323125.
Gómez, S., P. Zervas, D. G. Sampson, and R. Fabregat. 2014. "Context-Aware Adaptive and Personalized Mobile Learning Delivery Supported by UoLmP." *Journal of King Saud University - Computer and Information Sciences* 26 (1): 47–61. doi:10.1016/j.jksuci.2013.10.008.
Goodchild, M. F. 1992. "Geographical Information Science." *International Journal of Geographical Information Systems* 6 (1): 31–45. doi:10.1080/02693799208901893.
Goodchild, M. F. 2010. "Twenty Years of Progress: GIScience in 2010." *Journal of Spatial Information Science* 1 (1): 3–20.
Griffin, A. L., T. White, C. Fish, B. Tomio, H. Huang, C. R. Sluter, J. V. M. Bravo, et al. 2017. "Designing across Map Use Contexts: A Research Agenda." *International Journal of Cartography*: 1–25. doi:10.1080/23729333.2017.1315988.
Grifoni, P., A. D'Ulizia, and F. Ferri. 2018. "Context-Awareness in Location Based Services in the Big Data Era." In *Mobile Big Data,* edited by G. Skourletopoulos, G. Mastorakis, C. X. Mavromoustakis, C. Dobre, and E. Pallis. Cham: Springer. doi:10.1007/978-3-319-67925-9_5.
Gröger, G., and P. Lutz. 2012. "CityGML – Interoperable Semantic 3D City Models." *ISPRS Journal of Photogrammetry and Remote Sensing* 71: 12–33. doi:10.1016/j.isprsjprs.2012.04.004.
Guessoum, D., M. Miraoui, and C. Tadj. 2015. "Survey of Semantic Similarity Measures in Pervasive Computing." *International Journal on Smart Sensing and Intelligent Systems* 8: 1. doi:10.21307/ijssis-2017-752.
Hakobyan, L., J. Lumsden, D. O'Sullivan, and H. Bartlett. 2013. "Mobile Assistive Technologies for The Visually Impaired." *Survey Of Ophthalmology* 58 (6): 513-528.
Ham, N., A. Dirin, and T. H. Laine. 2017. "Machine Learning and Dynamic User Interfaces in a Context Aware Nurse Application Environment." *Journal of Ambient Intelligence and Humanized Computing* 8 (2): 259–271. doi:10.1007/s12652-016-0384-1.
Harrison, R., D. Flood, and D. Duce. 2013. "Usability of Mobile Applications: Literature Review and Rationale for a New Usability Model." *Journal of Interaction Science* 1 (1): 1. doi:10.1186/2194-0827-1-1.
Herrera, E. P. 2017. "Location-Based Technologies for Supporting Elderly Pedestrian in 'Getting Lost' Events." *Disability and Rehabilitation: Assistive Technology* 12 (4): 315–323. doi:10.1080/17483107.2016.1181799.
Hervás, R., J. Bravo, and J. Fontecha. 2010. "A Context Model Based on Ontological Languages: A Proposal ForInformation Visualization." *Journal of Universal Computer Science* 16 (12): 1539–1555. doi:10.3217/jucs-016-12-1539.
Hirtle, S. C., and M. Raubal. 2013. "Many to Many Mobile Maps." In *Cognitive and Linguistic Aspects of Geographic Space*, edited by M. Raubal, D. M. Mark, and A. U. Frank, 141–157. Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-34359-9_8.
Horta, E. T., I. C. Lopes, and J. J. P. C. Rodrigues. 2015. "Ubiquitous MHealth Approach for Biofeedback Monitoring with Falls Detection Techniques and Falls Prevention Methodologies." In *Mobile Health,*edited by S. Adibi. Cham: Springer. doi:10.1007/978-3-319-12817-7_3.
Huang, H. 2015. "Designing across Human Abilities and Map Use Contexts." In *ICC 2015 Workshop "Envisioning the Future of Interactive Cartography Research*." Curitiba: Brazil.

Huang, H. 2016. "Context-Aware Location Recommendation Using Geotagged Photos in Social Media." *ISPRS International Journal of Geo-Information* 5 (12): 195. doi:10.3390/ijgi5110195.

Huang, H., and G. Gartner. 2012. "Using Context-Aware Collaborative Filtering for POI Recommendations in Mobile Guides." In *Advances in Location-Based Services*, edited by G. Gartner and F. Ortag, 131–147. Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-24198-7_9.

Huang, H., G. Gartner, M. Schmidt, and L. Yan. 2009. "Smart Environment for Ubiquitous Indoor Navigation." *NISS 2009*, 176–180. IEEE doi:10.1109/NISS.2009.16.

Huang, H., M. Schmidt, and G. Gartner. 2012. "Spatial Knowledge Acquisition with Mobile Maps, Augmented Reality and Voice in the Context of GPS-Based Pedestrian Navigation: Results from a Field Test." *Cartography and Geographic Information Science* 39 (2): 107–116. doi:10.1559/15230406392107.

Huang, H., and S. Gao. 2018. "Location Based Services." In *The Geographic Information Science & Technology Body of Knowledge*, edited by J. P. Wilson. Ithaca, NY: UCGIS. doi:10.22224/gistbok/2018.1.14

Isikdag, U., and S. Zlatanova. 2009. "A SWOT Analysis on the Implementation of Building Information Models within the Geospatial Environment." In *UDMS Annual*, 2009, edited by A. Krek, M. Rumor, S. Zlatanova, and E. M. Fendel. London: CRC Press.

Jiang, B., and X. Yao. 2006. "Location-Based Services and GIS in Perspective." *Computers, Environment and Urban Systems* 30 (6): 712–725. doi:10.1016/j.compenvurbsys.2006.02.003.

Jing, Z., B. Freeman, and L. Mu. 2016. "Can Mobile Phone Apps Influence People's Health Behavior Change? An Evidence Review." *Journal of Medical Internet Research* 18 (11): e287. doi:10.2196/jmir.5692.

Jo, H., S. Kang, H. J. Kwon, and J. D. Lee. 2017. "In-Door Location-Based Smart Factory Cloud Platform Supporting Device-to-Device Self-Collaboration." *BigComp 2017*, 348–351. IEEE doi:10.1109/BIGCOMP.2017.7881691.

Kaikkonen, A., A. Kekäläinen, M. Cankar, and T. Kallio. 2008. "Will Laboratory Test Results Be Valid in Mobile Contexts?." In *Handbook of Research on User Interface Design and Evaluation for Mobile Technology*, edited by P. Zemliansky and K. St. Amant, 897–909. Hershey: IGI Global.

Kaulich, T., T. Heine, and A. Kirsch. 2017. "Indoor Localisation with Beacons for a User-Friendly Mobile Tour Guide." *KI - Künstliche Intelligenz* 31 (3): 239–248. doi:10.1007/s13218-017-0496-6.

Keler, A. 2017. "Traffic Pattern Analysis Framework with Emphasis on Floating Car Data (FCD)." PhD Thesis, University of Augsburg.

Kerski, J. 2016. "Location Privacy." *The Geographic Information Science & Technology Body of Knowledge*, edited by, J. P. Wilson. Ithaca, NY: UCGIS. doi:10.22224/gistbok/2016.3.2.

Kessler, C. 2010. *Context-Aware Semantics-Based Information Retrieval*. Amsterdam: IOS Press.

Kie, J. G., J. Matthiopoulos, R. A. John Fieberg, F. C. Powell, M. S. Mitchell, J.-M. Gaillard, and P. R. Moorcroft. 2010. "The Home-Range Concept: Are Traditional Estimators Still Relevant with Modern Telemetry Technology?" *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 365 (1550): 2221–2231. doi:10.1098/rstb.2010.0093.

Kim, H.-J., J. Cha, R. C. Park, T.-J. Nam, W. Lee, and G. Lee. 2016. "Mo-Bi: Contextual Mobile Interfaces through Bimanual Posture Sensing with Wrist-Worn Devices." In *HCI Korea*, Vol. 2016, 94–99. South Korea: Hanbit Media, Inc. doi:10.17210/hcik.2016.01.94.

Kozlovsky, J., J. Dvorak, and O. Krejcar. 2016. "Location Based Services Used in Smart Electronic Wallet Mobile Application." In *MobiWIS 2016*, edited by M. Younas, I. Awan, N. Kryvinska, C. Strauss, and D. van Thanh, 353–362. Cham: Springer. doi:10.1007/978-3-319-44215-0_30.

Krisp, J. M., and A. Keler. 2015. "Car Navigation – Computing Routes That Avoid Complicated Crossings." *International Journal of Geographical Information Science* 29 (11): 1988–2000. doi:10.1080/13658816.2015.1053485.

Kubo, Y., R. Takada, S. Buntarou, and S. Takahashi. 2017. "Exploring Context-Aware User Interfaces for Smartphone-Smartwatch Cross-Device Interaction." *IMWUT* 1 (3): 1–21. doi:10.1145/3130934.

Lam, L. D. M., A. Tang, and J. Grundy. 2016. "Heuristics-Based Indoor Positioning Systems: A Systematic Literature Review." *Journal of Location Based Services* 10 (3): 178–211. doi:10.1080/17489725.2016.1232842.

Lanir, J., A. J. Wecker, T. Kuflik, and Y. Felberbaum. 2016. "Shared Mobile Displays: An Exploratory Study of Their Use in a Museum Setting." *Personal and Ubiquitous Computing* 20 (4): 635–651. doi:10.1007/s00779-016-0931-y.

Lee, B., K. Yang, H. Lim, and N. Hur. 2015. "Mobile Multimedia Applications: Speech Enabled Location Based Data Services." *ICCE 2015*, 32–33. IEEE doi:10.1109/ICCE.2015.7066307.

Lee, J. 2004. "A Spatial Access-Oriented Implementation of A 3-D GIS Topological Data Model for Urban Entities." *GeoInformatica* 8 (3): 237–264. doi:10.1023/B:GEIN.0000034820.93914.d0.

Lee, J., L. Ki-Joune, S. Zlatanova, T. Kolbe, C. Nagel, and T. Becker. 2014. *OGC® IndoorGML*. Open Geospatial Consortium. http://docs.opengeospatial.org/is/14-005r5/14-005r5.html

Lee, W.-P., C.-T. Chen, J.-Y. Huang, and J.-Y. Liang. 2017. "A Smartphone-Based Activity-Aware System for Music Streaming Recommendation." *Knowledge-Based Systems* 131: 70–82. doi:10.1016/j.knosys.2017.06.002.

Li, C., and P. Longley. 2006. "A Test Environment for Location-Based Services Applications." *Transactions in GIS* 10 (1): 43–61. doi:10.1111/tgis.2006.10.issue-1.

Li, S., S. Dragicevic, F. A. Castro, M. Sester, S. Winter, A. Coltekin, C. Pettit, et al. 2016. "Geospatial Big Data Handling Theory and Methods: A Review and Research Challenges." *ISPRS Journal of Photogrammetry and Remote Sensing* 115: 119–133. doi:10.1016/j.isprsjprs.2015.10.012.

Li, Y., J. Wang, and L. Zhang. 2015. "LBS-Based Dilemma Zone Warning System at Signalized Intersection." In *Progress in Location-Based Services 2014*, edited by G. Gartner, and H. Huang, 223–237. Cham: Springer. doi:10.1007/978-3-319-11879-6_16.

Lorenz, B., H. J. Ohlbach, and E.-P. Stoffel. 2006. "A Hybrid Spatial Model for Representing Indoor Environments." In *W2GIS 2006*, 102–112. Berlin, Heidelberg: Springer. doi:10.1007/11935148_10.

Maia, L. F., C. Nolêto, M. Lima, C. Ferreira, C. Marinho, W. Viana, and F. Trinta. 2017. "LAGARTO: A LocAtion Based Games AuthoRing TOol Enhanced with Augmented Reality Features." *Entertainment Computing* 22: 3–13. doi:10.1016/j.entcom.2017.05.001.

Mathew, A., P. S. Amrutha, R. S. Jacob, S. S. Varghese, and D. M. Jose. 2017. "Adverto: A Location Based Advertising System." *Imperial Journal of Interdisciplinary Research* 3 (2): 1285–1287.

Meng, L., A. Zipf., and W. Stephan. 2007. *Map-Based Mobile Services : Interactivity and Usability*. Berlin, Heidelberg: Springer.

Mokbel, M. F., J. Bao, A. Eldawy, J. Levandoski, and M. Sarwat. 2011. "Personalization, Socialization, and Recommendations in Location-Based Services 2.0. "Paper presented at the 5th International Workshop on Personalized Access, Profile Management, and Context Awareness in Databases, Seattle, WA, September 2.

Montello, D., and M. Raubal. 2013. "Functions and Applications of Spatial Cognition." In *The APA Handbook of Spatial Cognition*, edited by D. Waller and L. Nadel, 249–264. Washington, DC: APA.

Montello Daniel, R. 2009. "Cognitive Research in GIScience: Recent Achievements and Future Prospects." *Geography Compass* 3 (5): 1824–1840. doi:10.1111/geco.2009.3.issue-5.

Ogi, T., K. Ito, and S. Ukegawa. 2018. "Multilingual Information Service Based on Combination of Smartphone and Digital Signage." In *NBiS 2017*, edited by L. Barolli, T. Enokido, and M. Takizawa, 644–653. Cham: Springer. doi:10.1007/978-3-319-65521-5_56.

Olteanu, A., C. Castillo, F. Diaz, and E. Kiciman. 2016. "Social Data: Biases, Methodological Pitfalls, and Ethical Boundaries." SSRN Scholarly Paper ID 2886526. Rochester, NY: Social Science Research Network.

Oviatt, S., P. R. Björn Schuller, D. S. Cohen, G. Potamianos, and A. Krüger, eds. 2017. *The Handbook of Multimodal-Multisensor Interfaces: Foundations, User Modeling, and Common Modality Combinations - Volume 1*. New York: ACM and Morgan & Claypool.

Ozdenizci, B., V. Coskun, and O. Kerem. 2015. "NFC Internal: An Indoor Navigation System." *Sensors* 15 (4): 7571–7595. doi:10.3390/s150407571.

Paay, J., and J. Kjeldskov. 2008. "Understanding the User Experience of Location-Based Services: Five Principles of Perceptual Organisation Applied." *Journal of Location Based Services* 2 (4): 267–286. doi:10.1080/17489720802609328.

Parush, A., S. Ahuvia, and I. Erev. 2007. "Degradation in Spatial Knowledge Acquisition When Using Automatic Navigation Systems." In *Spatial Information Theory*, Vol. 4736, edited by S. Winter, M. Duckham, L. Kulik, and B. Kuipers, 238–254. Berlin, Heidelberg: Springer.

Peng, E., P. Peursum, L. Ling, and S. Venkatesh. 2010. "A Smartphone-Based Obstacle Sensor for the Visually Impaired." In *UIC 2010*, edited by Z. Yu, R. Liscano, G. Chen, D. Zhang, and X. Zhou, 590–604. Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-16355-5_45.
Pham, A., K. Huguenin, I. Bilogrevic, I. Dacosta, and J.-P. Hubaux. 2016. "SecureRun: Cheat-Proof and Private Summaries for Location-Based Activities." *IEEE Transactions on Mobile Computing* 15 (8): 2109–2123. doi:10.1109/TMC.2015.2483498.
Pielot, M., B. Poppinga, W. Heuten, and S. Boll. 2011. "A Tactile Compass for Eyes-Free Pedestrian Navigation." In *Proceedings of INTERACT 2011*, edited by P. Campos, N. Graham, J. Jorge, N. Nunes, P. Palanque, and M. Winckler, 640–656. Berlin, Heidelberg: Springer-Verlag. http://dl.acm.org/citation.cfm?id=2042118.2042179.
Raper, J., G. Gartner, H. Karimi, and C. Rizos. 2007a. "A Critical Evaluation of Location Based Services and Their Potential." *Journal of Location Based Services* 1 (1): 5–45. doi:10.1080/17489720701584069.
Raper, J., G. Gartner, H. Karimi, and C. Rizos. 2007b. "Applications of Location–Based Services: A Selected Review." *Journal of Location Based Services* 1 (2): 89–111. doi:10.1080/17489720701862184.
Ratti, C., and M. Claudel. 2016. *The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life*. New Haven, CT: Yale University Press.
Raubal, M. 2011. "Cogito Ergo Mobilis Sum: The Impact of Location-Based Services on Our Mobile Lives." In *The SAGE Handbook of GIS and Society*, edited by T. L. Nyerges, H. Couclelis, and R. McMaster, 159–174. London: SAGE Publications . doi:10.4135/9781446201046.n9.
Raubal, M., and I. Panov. 2009. "A Formal Model for Mobile Map Adaptation." In *Location Based Services and TeleCartography II*, 11–34. Berlin Heidelberg: Springer. doi: 10.1007/978-3-540-87393-8_2.
Rautaray, S. S., and A. Agrawal. 2015. "Vision Based Hand Gesture Recognition for Human Computer Interaction: A Survey." *Artificial Intelligence Review* 43 (1): 1–54. doi:10.1007/s10462-012-9356-9.
Rehman, U., and S. Cao. 2017. "Augmented-Reality-Based Indoor Navigation: A Comparative Analysis of Handheld Devices versus Google Glass." *IEEE Transactions on Human-Machine Systems* 47 (1): 140–151. doi:10.1109/THMS.2016.2620106.
Reilly, D., B. Mackay, C. Watters, and K. Inkpen. 2009. "Planners, Navigators, and Pragmatists: Collaborative Wayfinding Using a Single Mobile Phone." *Personal and Ubiquitous Computing* 13 (4): 321–329. doi:10.1007/s00779-008-0207-2.
Retscher, G., and F. Roth. 2017. "Wi-Fi Fingerprinting with Reduced Signal Strength Observations from Long-Time Measurements." In *Progress in Location-Based Services 2016*, 3–25. Springer. doi:10.1007/978-3-319-47289-8_1.
Richter, K. F., D. Dara-Abrams, and M. Raubal. 2010. "Avigating and Learning with Location Based Services: A User-Centric Design." In *LBS 2010*. Guangzhou, China.
Robinson, A. C., A. B. Urška Demšar, A. B. Moore, B. Jiang, K. Field, M.-J. Kraak, S. P. Camboim, and C. R. Sluter. 2017. "Geospatial Big Data and Cartography: Research Challenges and Opportunities for Making Maps that Matter." *International Journal of Cartography, March* 1–29. doi:10.1080/23729333.2016.1278151.
Rukzio, E., M. Müller, and R. Hardy. 2009. "Design, Implementation and Evaluation of a Novel Public Display for Pedestrian Navigation." In *Proceedings of CHI 2009*, 113. New York: ACM Press. doi:10.1145/1518701.1518722.
Sailer, C., P. Kiefer, J. Schito, and M. Raubal. 2016. "Map-Based Visual Analytics of Moving Learners." *International Journal Mob Human Computation Interact* 8 (4): 1–28. doi:10.4018/IJMHCI.
Santana, J. M., J. Wendel, A. Trujillo, J. P. Suárez, A. Simons, and A. Koch. 2017. "Multimodal Location Based Services—Semantic 3D City Data as Virtual and Augmented Reality." In *Progress in Location-Based Services 2016*, edited by G. Gartner and H. Huang, 329–353. Cham: Springer. doi:10.1007/978-3-319-47289-8_17.
Scellato, S., A. Noulas, R. Lambiotte, and C. Mascolo. 2011. "Socio-Spatial Properties of Online Location-Based Social Networks." In *Proceedings of ICWSM*, 329–336. AAAI.
Schmidt, A., M. Beigl, and H.-W. Gellersen. 1999. "There Is More to Context than Location." *Computers & Graphics* 23 (6): 893–901. doi:10.1016/S0097-8493(99)00120-X.

Schneider, C., S. Zutz, K. Rehrl, R. Brunauer, and S. Gröchenig. 2016. "Evaluating Gps Sampling Rates for Pedestrian Assistant Systems." *Journal Of Location Based Services* 10 (3): 212-239. doi: 10.1080/17489725.2016.1259509.

Schou, S. 2008. "Context-Based Service Adaptation Platform: Improving the User Experience Towards Mobile Location Services." *ICOIN 2008*, 1–5. IEEE doi:10.1109/ICOIN.2008.4472797.

Shaw, S.-L., M.-H. Tsou, and Y. Xinyue. 2016. "Editorial: Human Dynamics in the Mobile and Big Data Era." *International Journal of Geographical Information Science* 30 (9): 1687–1693. doi:10.1080/13658816.2016.1164317.

Shen, H., K.-Y. Chan, J. Coughlan, and J. Brabyn. 2008. "A Mobile Phone System to Find Crosswalks for Visually Impaired Pedestrians." *Technology and Disability* 20 (3): 217–224.

Slingsby, A., and J. Raper. 2008. "Navigable Space in 3D City Models for Pedestrians." In *Advances in 3D Geoinformation Systems*, edited by P. van Oosterom, S. Zlatanova, F. Penninga,and E. M. Fendel, 49–64. Berlin, Heidelberg: Springer. doi:10.1007/978-3-540-72135-2_3.

Steiniger, S., M. Neun, and A. Edwardes. 2006. "Foundations of Location Based Services." http://www.e-cartouche.ch/content_reg/cartouche/LBSbasics/en/text/LBSbasics.pdf.

Stepnowski, A., L. Kamiński, and J. Demkowicz. 2011. "Voice Maps: The System for Navigation of Blind in Urban Area." In *ACACOS'11*, 201–206. Stevens Point: World Scientific and Engineering Academy and Society (WSEAS).

Strang, T., and C. Linnhoff-Popien. 2004. "A Context Modeling Survey. "Paper presented at the Workshop on Advanced Context Modelling, Reasoning and Management at UbiComp 2004, Nottingham, UK, September 7.

Tiina, S. L., and A.-M. Nivala. 2005. "Adaptation to Context — A Way to Improve the Usability of Mobile Maps." In *Map-Based Mobile Services*, 107–123, edited by L. Meng, T. Reichenbacher, and A. Zipf. Berlin/Heidelberg: Springer-Verlag. doi:10.1007/3-540-26982-7_8.

Tsai, T.-H., C.-Y. Shen, Z.-S. Lin, H.-R. Liu, and W.-K. Chiou. 2017. "Exploring Location-Based Augmented Reality Experience in Museums." In *UAHCI 2017*, edited by M. Antona and C. Stephanidis, 199–209, Cham: Springer. doi:10.1007/978-3-319-58703-5_15.

Vanclooster, A., N. Van de Weghe, and D. M. Philippe. 2016. "Integrating Indoor and Outdoor Spaces for Pedestrian Navigation Guidance: A Review." *Transactions in GIS* 20 (4): 491–525. doi:10.1111/tgis.2016.20.issue-4.

Wenig, N., D. Wenig, S. Ernst, R. Malaka, B. Hecht, and S. Johannes. 2017. "Pharos: Improving Navigation Instructions on Smartwatches by Including Global Landmarks." *Proceedings of MobileHCI '17*, 1–13. New York: ACM. doi:10.1145/3098279.3098529.

Wolf, K., M. Funk, P. Knierim, and L. Markus. 2016. "Survey of Interactive Displays through Mobile Projections." *International Journal of Mobile Human Computer Interaction* 8: 4. doi:10.4018/IJMHCI.

Yang, L., and M. Worboys. 2011. "A Navigation Ontology for Outdoor-Indoor Space: (Work-In-Progress)." In Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness, 31–34. ISA '11. New York, NY, USA: ACM. doi: 10.1145/2077357.2077364.

Yoon, S., J. Kim, and D. J. Connolly. 2017. "Understanding Motivations and Acceptance of Location-Based Services." *International Journal of Hospitality & Tourism Administration, May* 1–23. doi:10.1080/15256480.2017.1305316.

Yuan, Y., M. Raubal, and Y. Liu. 2012. "Correlating Mobile Phone Usage and Travel Behavior – A Case Study of Harbin, China." *Computers, Environment and Urban Systems* 36 (2): 118–130. doi:10.1016/j.compenvurbsys.2011.07.003.

Yurur, O., C. H. Liu, V. C. Zhengguo Sheng, M. Leung, W. Moreno, and K. K. Leung. 2016. "Context-Awareness for Mobile Sensing: A Survey and Future Directions." *IEEE Communications Surveys & Tutorials* 18 (1): 68–93. doi:10.1109/COMST.2014.2381246.

Zhang, S., S. M. Freundschuh, K. Lenzer, and P. A. Zandbergen. 2017. "The Location Swapping Method for Geomasking." *Cartography and Geographic Information Science* 44 (1): 22–34. doi:10.1080/15230406.2015.1095655.

Zhao, H., S. Winter, and M. Tomko. 2017. "Integrating Decentralized Indoor Evacuation with Information Depositories in the Field." *ISPRS International Journal of Geo-Information* 6 (7): 213. doi:10.3390/ijgi6070213.

Zheng, Y. 2011. "Location-Based Social Networks: Users." In *Computing with Spatial Trajectories*, edited by Y. Zheng and X. Zhou, 243–276. New York: Springer. doi:10.1007/978-1-4614-1629-6_8.

Zheng, Y., L. Capra, O. Wolfson, and H. Yang. 2014. "Urban Computing: Concepts, Methodologies, and Applications." *ACM Transactions on Intelligent Systems and Technology* 5 (3): 1–55. doi:10.1145/2629592.