Context Modeling and Processing in Location Based Services: Research Challenges and Opportunities

Haosheng Huang[1], Yi Cheng[2], Weihua Dong[3], Georg Gartner[4], Jukka M. Krisp[5], Liqiu Meng[6]

[1]Department of Geography, Ghent University, Belgium

[2]Information Engineering University, China

[3]Faculty of Geographical Science, Beijing Normal University, China

[4]Research Group Cartography, TU Wien, Austria

[5]Institute of Geography, Augsburg University, Germany

[6]Chair of Cartography and Visual Analytics, Technical University of Munich, Germany

Abstract:

To ensure good usability, Location Based Services (LBS) should be context-aware, i.e., adapting the information and services according to the context of their user, such as his/her location, tasks, preferences, and the underlying geo-social environment. This article reviews the main challenges related to the context modelling and processing in LBS, and proposes a list of essential research opportunities that can be pursued to overcome the challenges. These research challenges and opportunities are classified into 4 groups: “modelling of the geo-social environment”, “modelling of the mobile user”, “context-aware adaptation”, and “ethical data modelling and processing”. Sufficiently addressing these issues will enable LBS to provide “5R”, i.e., the “right” information, in the “right” way, at the “right” time, in the “right” place, to the “right” person.

Keywords:

Location based services, mobile data management, research agenda, context modelling, context-aware computing, location privacy

1. Introduction

We are living in a mobile information era when (mobile) information communication technologies are fundamentally changing science and society. *Location Based Services* (LBS), which are computer applications (especially mobile computing applications) deliver information tailored to the location and context of the device and the user (Huang et al., 2018), play a key role in this mobile information era. Recent years have seen rapid advances in LBS with the continuous evolvement of mobile devices, communication technologies, internet of things, and location big data (LocBigData). LBS have become increasingly popular, not only in outdoor environments, but also in many indoor environments, such as airports, big shopping malls, complex transportation hubs, and hospitals. More and more LBS are entering into general public's daily lives, with many application fields, such as navigation and mobility, emergency and disaster management, infotainment (e.g., gaming and social networking), healthcare, tracking and assistive technologies (Huang, 2022). As a result, LBS have attracted significant research attention from the disciplines of Cartography and Geographic Information Science (GIScience), as well as many neighboring disciplines.

Several key research trends can be identified in the interdisciplinary research domain of LBS (Huang et al., 2018), mainly on the aspects of application domains, usage environments, context-awareness, user interfaces, user experiences, and social and ethical issues.

- In terms of application domains, while navigation systems and mobile guides continue to be some main LBS applications and are still being improved (e.g., inclusion of real-time traffic information in navigation systems), more diverse applications have been emerging in recent years, including social networking, location-based gaming, healthcare and fitness monitoring, assistive technologies (e.g., for visually impaired or mobility impaired people), education (Zahtila & Burghardt, 2022), emergency response (Sun et al., 2021), and disaster management. Recently, the application domains of LBS are also being expanded into contact tracing or measure enforcement with the aims to help combat COVID-19 (Gupta et al., 2021; Min-Allah et al., 2021; Nguyen et al., 2020).
- Regarding the usage environments, there is an increasing trend in expanding LBS from outdoor to both outdoor and indoor environments (e.g., airports, museums/exhibitions, shopping malls, complex transport hubs, and hospitals). This is mainly due to the fact that recent years have seen significant advances in indoor positioning (e.g., with WiFi, Bluetooth low energy BLE, geomagnetic, or even acoustic signals) (Abid & Lefebvre, 2021; Chen et al., 2021), as well as the increasing availability of indoor GIS and BIM data, e.g., at OpenStreetMap.
- There is also a trend towards incorporating more context information (beyond location) to provide context-aware LBS. Such additional context information includes those related to users' tasks, preferences, social situations, and even emotion status, as well as those related to the underlying geo-social environments (Griffin et al., 2017; Grifoni et al., 2018a; Sarjakoski & Nivala, 2005). Such context-aware LBS are enabled by the recent advances in the context-sensing abilities of mobile devices (e.g., allowing to capture users' gaze behaviors, activities and physiological/physiopsychological status), the increasingly smart environments (e.g., enriched with various types of sensors), and the high availability of huge amount of location big data (e.g., location tracking data, social media data, and crowdsourced geographic information) (Huang et al., 2021).
- There is also a trend towards non-intrusive user interfaces in LBS, which allow users to obtain the relevant information in a more "natural" way (e.g., without interrupting users' tasks or on-going activities). While mobile maps and auditory on smartphones or in-car (navigation) devices continue to be the main communication forms and are still being improved, more diverse forms are being introduced for LBS applications, such as augmented/mixed reality (AR/MR) (Cao et al.,

2023; B. Liu et al., 2021) and haptics. More types of mobile and wearable devices are emerging for recent LBS applications, such as smartwatches (Perebner et al., 2019), head-mounted displays (HMDs), and digital glasses, as well as the seamless combination of different devices.

- Further literature is focusing on the usability, privacy, and social aspects of LBS. Usability evaluation with intended users has become a "default action" when developing LBS. Such user experience studies are implemented in labs (e.g., in virtual environments) and real-world application fields, employing conventional empirical methods (e.g., focus groups, think aloud, performance assessment, interviews, screen/user logging) and new logging devices (e.g., eye-tracking glasses, Electroencephalography EEG devices). There is also increasing research attention being paid to the potential "side effects" of LBS (e.g., navigation systems) on our spatial memory and abilities (Huang et al., 2012; Wunderlich et al., 2023). In recent years, especially in the context of employing contact tracing to help combating COVID-19, many studies focus on issues related to location privacy, ethical issues, and user acceptances of such LBS applications (Dreyer et al., 2022; Gupta et al., 2021; Roche, 2020; Yao et al., 2023).

From a high-level perspective, LBS are parts of the current paradigm of ubiquitous computing with a special focus on the importance of location-awareness. The scientific fields of LBS contribute to the vision that makes computation or "services" accessible anytime, anywhere, for anyone and anything (referred to as "4A") to benefit our human society and environment. To enable "4A" services, LBS, and ubiquitous computing in general, should be developed to provide "5R", i.e., "right" information, in the "right" way, at the "right" time, in the "right" place, to the "right" person. While significant advances have been made in the domain of LBS (as outlined above), there still exist a lot of basic and applied research questions considering the vision of 4A services and the 5R requirements.

Based on a bottom-up approach, Huang et al. (2018) proposed a series of open "key research challenges" that are essential for further development of LBS, setting a research agenda for LBS to "positively" shape the future of our mobile information society. These research challenges can be classified into 6 categories: ubiquitous positioning; context modelling and context-awareness; mobile user interface and interaction; user studies and evaluation; analytics of location-based big data; and social/behavioral implications of LBS. Within this article, we aim to provide a detailed review of the challenges and opportunities in the category of "context modelling and context-aware adaptation". More specifically, we will focus on the modelling of the user and his/her environment (i.e., creating a representation or abstraction of the user and environment), and how such representations are used to identify information matching the user's context. Together with the research agenda on mobile map design (Roth et al.) and cognitive issues of mobile map usage (Griffin et al.) in this special issue, this article aims to comprehensively address the essential research challenges in LBS.

In the following, we begin by describing "what is special about location-based services" and how such distinct characteristics matter (Section 2). In Section 3, we discuss the general aspect of data and processing in LBS. In Section 4, we summarize the open challenges and opportunities related to data modelling and processing in LBS. Finally, Section 5 concludes the article.

2. What is special about location-based services (LBS)?

For the provision of LBS, several main tasks need to be dealt with, including determining the location of a user or an object (i.e., positioning), modelling the user's contexts to identify the relevant information to satisfy their information needs, and communicating the relevant information to the user (e.g., via mobile maps, augmented reality, voices, and haptics). Due to the interdisciplinary nature of these core tasks, several main scientific domains have significantly contributed to the research advances of LBS, including the discipline of GIScience and cartography, as well as the sister disciplines like (engineering) geodesy and computer science (particularly ubiquitous computing, Internet technology, and human-computer interaction). Among all these disciplines, GIScience and cartography, due to its strong focus on the modelling, analyzing, and communicating of location information, play a more prominent role in LBS.

Compared with conventional geographic information systems (GIS) and web mapping applications, LBS present several distinct characteristics, in terms of "users and tasks", "dynamic and mobile", and "context-awareness" (Huang, 2022). First, users of LBS might be non-specialists with very limited GIS expertise, and they often employ LBS to support their daily activities in space, e.g., localization, navigation, information/location searching, and entertainment. However, LBS are also used by many specialists from different backgrounds for various professional tasks, such as field/resources/facilities surveying, precision agriculture, disaster response and management, and mobile healthcare. Second, LBS are often used in a dynamic and mobile environment, and via mobile portable devices, which often have limited screen sizes, computing power, and interaction capacity. LBS users sometimes are also constrained by the available time, and need to make time-critical decision in-situ. Thirdly, LBS are (or should be) aware of the context their users are currently in, and can adapt the information and its presentation manner accordingly.

These distinct characteristics of LBS pose many new research challenges to the conventional GIScience and cartography research communities and other cognate communities. For example, in terms of "users and tasks", research attentions should be paid to user profiling and task modelling (considering the user's preferences, interests, information needs, level of expertise, and tasks), quantitative and qualitative representation of (location) information (e.g., employing a "naïve geography" approach (Egenhofer & Mark, 1995)), and privacy-preserving and ethical data modelling and processing (e.g., to increase the user acceptance of LBS). Regarding the "dynamic and mobile" nature, it is essential for LBS to model the dynamics of geo-social environment and the cognition capacity of users (e.g., especially in time-critical tasks like transit from a subway to a train in a complex transportation hub), as well as to balance the distribution of data and processing over mobile devices and the cloud. Finally, to enable "context-awareness", methods related to (real-time) context acquisition, context modelling, and context-aware adaptation should be developed.

3. Context and data processing pipeline in LBS

LBS are developed to assist a mobile user's tasks and fulfil their information needs at various environments. To ensure good usability, LBS should be context-aware, i.e., adapting the information and services according to the context of their user. Context is "any information that can be used to characterize the situation of an entity, and an entity is a person, place or object that is considered relevant to the interaction between a user and an application" (Dey, 2001, p. 5).

In general, contexts in LBS can be classified into two groups: those about the geo-social environment where the LBS is being used, and those related to the mobile user. Correspondingly, two types of data are commonly represented and modelled in LBS (Figure 1): Data about the geo-social environment (referring to the combination of natural/physical and social environments), and data about the mobile user. Examples of the first type of data refer to affordance of the geo-social environment (i.e., what the environment offer), how people act and behave there, what was/is/will be (happening) there, and so on. The second type of data describes the personal context of the mobile user, e.g., the user's tasks, preferences, physio- and psychological status (e.g., gaze behaviors, emotion status), what activity they were and are doing, property of their mobile device(s), and so on.

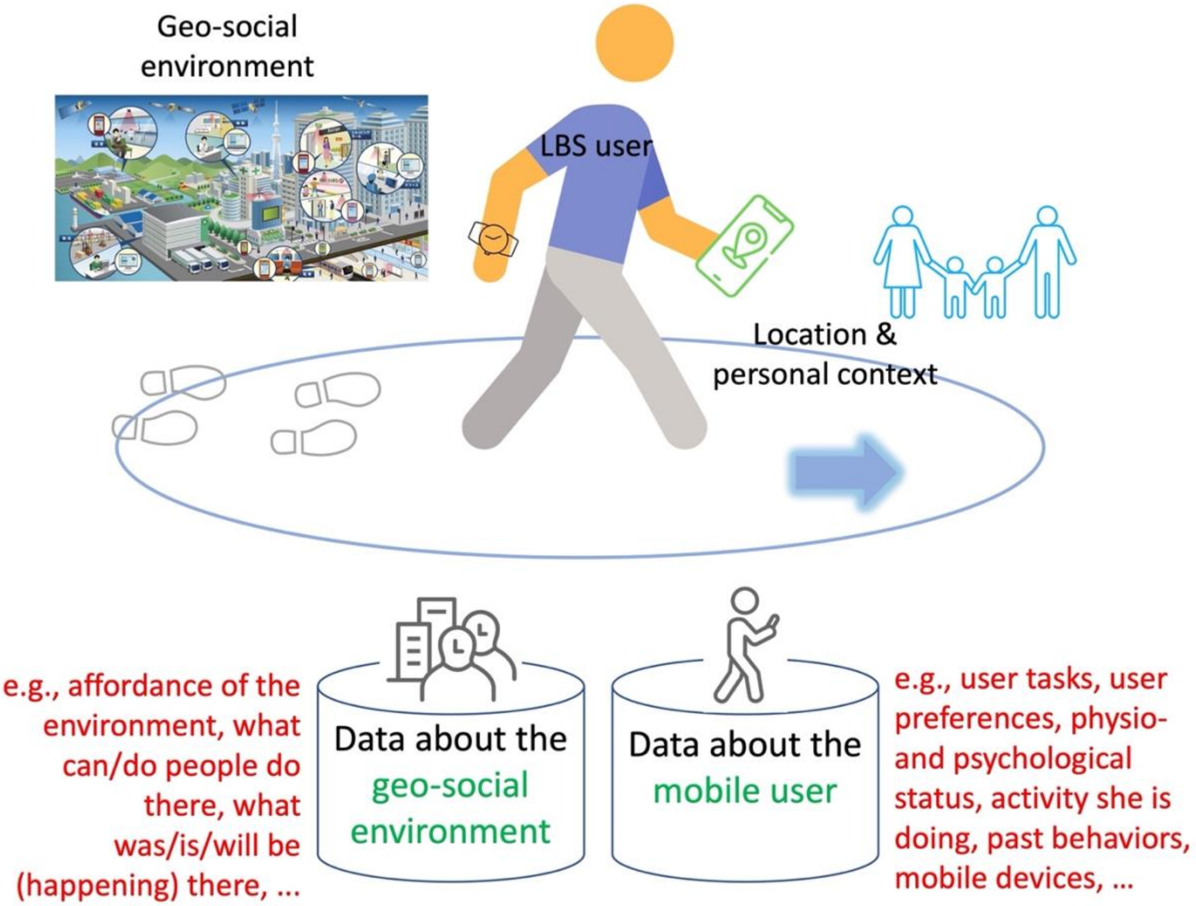

Figure 1. To provide a mobile user with relevant information (and thus fulfil their information needs), LBS needs to deal with two types of contexts/data: those about the geo-social environment where the LBS is being used and those about the user. The upper part of the figure is adapted from Steiniger et al. (2006) at CartouCHe (http://www.e-cartouche.ch/) under CC BY 2.0.

Figure 1 Alt Text: Two types of contexts/data are commonly represented and modelled in LBS, including those about the geo-social environment where the LBS is being used (referring to the combination of natural/physical and social environments), and those about the mobile user.

Taking LBS applications designed for guiding tourists in a city as an example, all attractions (points of interests, e.g., museums, historical sites, parks) in the environment, their information and descriptions, current events in the city, and other ("like-minded") tourists' "footprints" need to be modelled to capture the characteristics of the geo-social environment. Meanwhile, information regarding the user's preferences, social situations (e.g., alone or with children), available time, and other personal context information needs to be included as well in the data model.

As mentioned, modelling these two types of contexts/data and their dynamics requires integration of various data sources, ranging from sensor outputs, basic geodata (e.g., topographical data), statistical data, to location big data (e.g., social media data, crowdsourced geographic information).

Figure 2 shows a typical data processing pipeline in LBS. After modelling these two types of contexts/data, LBS applications then need to apply a series of data reasoning, filtering, and adapting steps to identify what information is relevant and thus needed to be communicated to the mobile user. The relevant information identified and extracted is then communicated to the mobile user, via appropriate communication forms and devices (e.g., mobile maps on smartphones or smartwatches, AR/MR), employing techniques of (mobile) human-computer interaction and cartographic design.

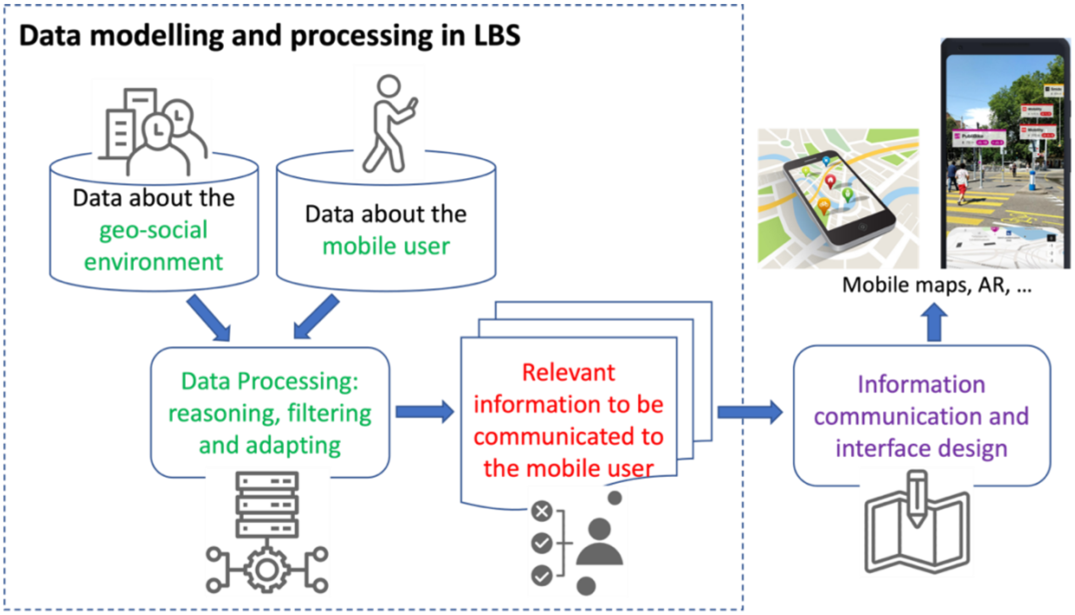

Figure 2. Context modelling and processing pipeline in LBS, leading to the selection of relevant information and the communication of such relevant information.

Figure 2 Alt Text: Data about the geo-social environment and the mobile user need to be further processed in LBS to identify what information is relevant and thus needed to be communicated to the mobile user.

4. Research challenges and opportunities

At a high-level, the essential question that is persistent for the context modelling and processing in LBS is: *How can relevant information that best fits a user's context be identified*? Here, a user is usually a human, but can be expanded to an intelligent agent, e.g., in the context of autonomous cars and artificial intelligence.

In the following, we outline long-term research challenges regarding context modelling and processing in LBS, organized into four broad areas (Figure 3): (1) modelling of the geo-social environment where the LBS is being used; (2) modelling of the mobile user; (3) context-aware adaptation; and (4) ethical data modelling and processing. For each broad area, we present the leading research challenge, and then propose a series of research opportunities that address this overall challenge, i.e., key research topics (potentially in a nearer term) that can be pursued to overcome the challenge. We do not particularly focus on specific types of LBS applications, as sufficiently addressing these challenges would prepare LBS to be ready for different kinds of applications.

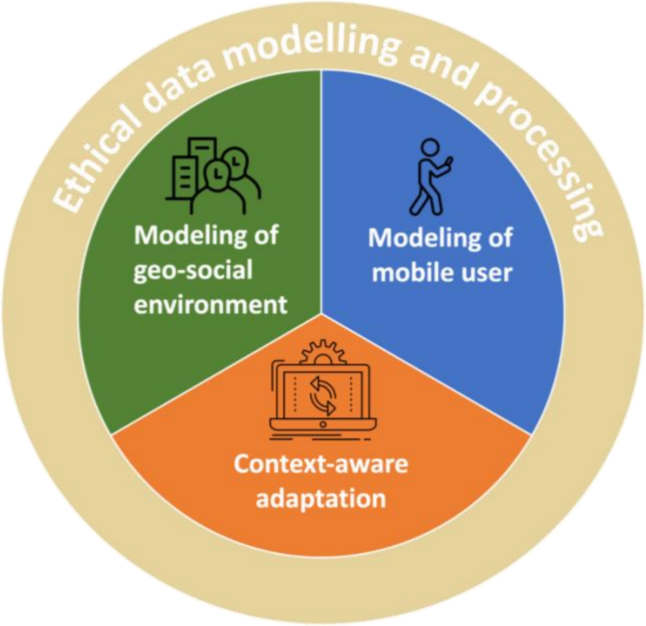

Figure 3. The "key research challenges" regarding context modelling and processing in LBS, organized into four broad areas: modelling of geo-social environment; modelling of mobile user; context-aware adaptation; and ethical data modelling and processing. Note that the first two focus on the modelling of two types of contexts/data: those related to the geo-social environment where the LBS is being used, and those about the personal context of the mobile user. The 3rd area "context-aware adaptation" further processes these two types of contexts/data to identify the most relevant information to fits

his/her context. The last field is an overarching area that emphasizes the importance of considering privacy and ethics during context modelling and processing.

Figure 3 Alt Text: There are four key research challenges on context modelling and processing in LBS, including modelling of geo-social environment; modelling of mobile user; context-aware adaptation; and ethical data modelling and processing.

4.1 Modelling of the geo-social environment

The underlying geographic environment, in which the LBS application is being used, determines the user's behaviors and what they can be expected there. Therefore, data about the geographic environment very often form the information space, out of which relevant information that should be communicated to the user can be derived. An overarching research challenge is: *How can the geo-social environment be modelled to effectively support LBS?*

We specifically use the term *geo-social environment* to refer to the combination of the physical geographic environment (e.g., what are there physically, what technical infrastructure is accessible there) and the social environment (e.g., how do people behave there, what can people do there, what was/is/will be (happening) there). While aspects related to the physical geographic environment are the typical focus of GIS data modelling, and have been stored in many existing basic geospatial data sources (e.g., topographic data and road network data), the social aspects that describe how people behave in, use, experience, and perceive the environment are only starting to capture research attention in recent years. In the following, we present a series of research opportunities that help to overcome this overall challenge of modelling of the geo-social environment.

Opportunity 1.1: Indoor/outdoor seamless spatial modelling (high definition and 3D)

Effective modelling of the physical environment is needed to support various user queries in LBS. Spatial modelling of outdoor environments has been standardized to some extent (Kresse et al., 2022), and many basic geospatial data describing the geographic space and road networks are available as open data, e.g., via OpenStreetMap and many open government data. However, highly accurate and detailed modelling of the 3D environment (also known as *high-definition HD maps* for autonomous vehicles) (Meng, 2022; Rehrl et al., 2022), covering both geometrical information and semantic information, is still largely missing, and poses many research challenges. High accuracy concerns the degree or closeness to which the recorded spatial data of the environment match the values in the real world. It can be referred to the 3D geometrical information of an object in the environment (i.e., geometrical accuracy, e.g., at decimeter-level or even centimeter-level), but it can be also referred to non-spatial attributes of the object (i.e., conceptual accuracy). In terms of rich detail, taking road networks as an example, such modelling requires inclusion of more aspects of road networks (in addition to their geometries), such as the number of lanes, road shape, road surface and their quality, road marking, traffic signs, barriers, and other infrastructure elements. Such high definition (HD) road maps are essential for enabling lane-level navigation, wheelchair-based navigation, as well as autonomous driving and advanced driver-assistance systems in the short future. While on-going research efforts have been focused on HD road maps from autonomous driving perspectives (e.g., with various sensors like Lidar and radar), research efforts should be also paid to modelling other areas of the environment, as well as from the human users' perspectives, especially those of the pedestrians, cyclists, and car drivers/passengers (Guan et al., 2023). Another stringent requirement is that techniques and technologies of creating and maintaining such highly accurate and detailed maps must be low-cost (in terms of resources and time) and be applicable to large-scale environments. High resolution street-level images, e.g., street-view images or images from webcams, might be potentially a very interesting data source.

Meanwhile, significant research attention should be also paid to the spatial modelling of indoor environments. A number of indoor space models have been proposed from different disciplines and perspectives (Afyouni et al., 2017; Zhou et al., 2022), such as CityGML, building information models (BIM), and network models, without explicitly addressing the geometrical and semantical requirements introduced by indoor LBS. For example, for LBS to effectively support indoor wayfinding, indoor landmarks (salient spatial objects in the environment), physical signages, types of the navigation paths (e.g., wheelchair accessibility), etc. need to be modelled. Given that indoor spaces are often fragmented, enclosed, clustered and multi-storey (Zhou et al. 2022), to effectively support LBS applications (especially for those requiring information about the visibility of indoor objects, such as indoor wayfinding and evacuation) in indoor environments, the 3rd dimension of the environment should be carefully modelled. Research efforts should be also 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. An open research question is: Do we need to define a specific indoor spatial data model to accommodate each specific type of indoor LBS applications? Or does a generic data model that supports different LBS applications exist? Again, techniques and technologies that are at a low cost and applicable to various 3D indoor environments should be prioritized.

The dynamic nature of many geographic spaces also poses challenges in the spatial modelling of such outdoor and indoor environments. We need technologies that automatically capture the changes and update the data. Meanwhile, given that many LBS applications are used in mixed outdoor and indoor environments, spatial models that seamlessly integrate outdoor and indoor data models are urgently needed. A prominent challenge here is on the data heterogeneity: Outdoor and indoor spatial data often come from different sources, using different data formats, schemas, and coordinate systems. Integrating these diverse datasets requires data harmonization, which can be complex and time-consuming. To provide seamless user experiences, effective visualization techniques and user interfaces are also essential to ensure a smooth and intuitive experience for users.

Opportunity 1.2: Social sensing

As mentioned before, modelling the social aspects of the geographic environment, e.g., people's behavioral and social activities in space, is also essential for LBS applications. Examples of such social aspects include human mobility, social interaction, social-economic activities, city dynamics, or even governmental policies/measures and cultural issues. Recently, the increasing availability of *location-based big data* (LocBigData), such as location tracking or sensing data, social media data, crowdsourced geographic information, has enabled the modelling of such social aspects (Huang et al., 2021; Y. Liu et al., 2015). How can such social aspects be computationally extracted and effectively modelled for various LBS applications, considering the inherent biases, uncertainties, vagueness, and subjectiveness of LocBigData? New data analytic and modelling methods that take care of the above issues should be developed. Given that many unstructured LogBigData sources become available, such as texts (e.g., social media data in natural language), images (e.g., street-view images), and videos (e.g., those from webcams), methods developed in other fields such as natural language processing and computer visions (e.g., image semantic segmentation) should be also integrated and extended. Meanwhile, in addition to the modelling of "what happened or what is happening" at an environment, it is also essential to focus on the prediction of "what might happen in the (short) future", which will allow LBS applications to provide "anticipatory services" to improve user experiences. An example of such "anticipatory services" is navigation systems that proactively plan a route by avoiding the traffic jams that is predicted to be happened, e.g., in the 15 minutes, instead of mainly based on the current traffic situation (like in existing navigation systems, e.g., Google Maps) and only adjusting the route when a traffic jam occurs.

Furthermore, given the increasing popularity of online activities and behaviors, it may also be insightful to investigate how human behavior and social interaction in physical environments are linked to and mirrored in those in virtual environments, and how such integration (e.g., online to offline/physical, and offline to online) can be modelled for LBS.

4.2 Modelling of the mobile user

While data about the environment can be used to model the geo-social context in which the LBS application is being used, another essential task in LBS is to model the mobile user's personal context (Figure 4), including the user himself/herself (e.g., their interests and preferences, constraints, familiarity with the environment, cognitive and emotion status), their tasks/goals/needs/purpose of use, their current location, location histories, time (e.g., time of the day, day of the week, and season), social situations (e.g., who is with the user, and social relationships), and their mobile devices (e.g., their technical properties like screen sizes, interaction modality, and network connectivity), etc. *How can a mobile user's personal context, as well as its dynamics be modelled?*

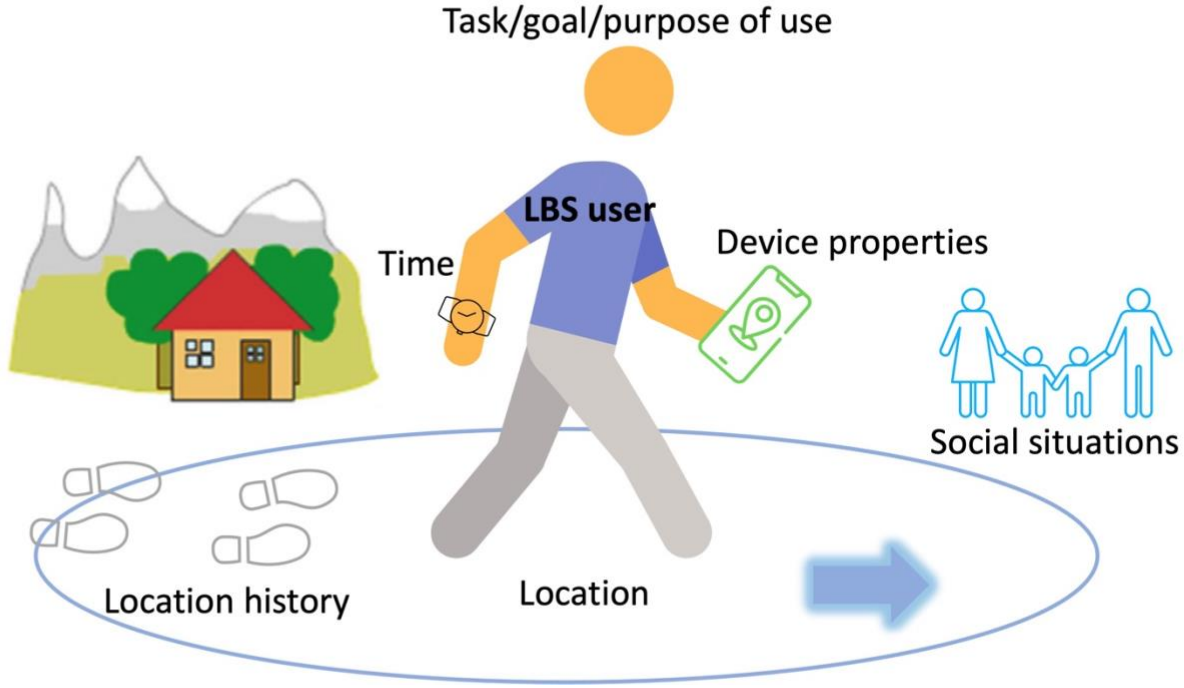

Figure 4. An LBS user and his/her personal context; Figure adapted from Steiniger et al. (2006) at CartouCHe (http://www.e-cartouche.ch/) under CC BY 2.0.

Figure 4 Alt Text: An LBS user and his/her personal context, including location, time, his/her task/goal/purpose of use, social situations (e.g., who is with him/her), device properties, and so on.

Opportunity 2.1: Ubiquitous positioning

Positioning, i.e., determine the location of a user or a spatial object, plays an essential role in LBS. To enable 4A services, ubiquitous positioning is needed to provide an accurate, reliable, and timely estimate of a user's or an object's location in all environments at all times. While Global Navigation Satellite Systems GNSS (e.g., GPS, GLONASS, Galileo, and Beidou) are widely available in many outdoor environments with various positioning accuracies, achieving accurate and reliable positioning in indoor environments, dense urban environments, and the underground is still a persistent technical challenge, despite recent advances in indoor positioning. From an end user's perspective, two stringent requirements need to be met for any indoor positioning technologies: easy-to-use (e.g., without the installation of additional hardware/software and complex configuration); and affordable (e.g., low cost or no explicit cost for the end user). Failing to meet the above two requirements will significantly hinder the applications of indoor LBS. Currently universal solutions (like GPS for outdoor environments) seem to be unrealistic for all indoor environments globally or regionally. Therefore, research should be also done to "standardize" the service interface of various indoor positioning solutions to enable the seamless integration of such solutions. This will allow an LBS application to work smoothly across different indoor environments despite the different positioning solutions that are deployed. Meanwhile, as in the "Opportunity 1.1 Indoor/outdoor seamless spatial modelling", it also makes sense to explore whether universal coordinate reference systems for indoor environments can be developed to allow the seamless integration of outdoor coordinates and indoor coordinates, enabling mixed outdoor and indoor applications.

Opportunity 2.2: Semantic enrichment of location

While positioning techniques typically provide the geometric coordinates in some spatial reference systems (very often latitude/longitude pairs in WGS-84 reference system for outdoor environments and numeric coordinates other local reference systems for indoors), such geometric coordinates often need to be semantically enriched. For example, a WGS-84 lat/lon coordinate "50.894879, 4.341482" is an abstract concept and hard to be understood by the general public. Adding semantics like "*it is located at the front of Atomium, in Brussel, Belgium; Having nine 18-meter-diameter stainless steel clad spheres, Atomium is landmark building in Brussel; you can climb to the top of Atomium to get a good overview of the city; it is also where I first met my best friend*" would make the location meaningful and allow people to better understand where the location is. In other words, such semantic enrichment of location adds meanings to the abstract geometric coordinates, and better enables LBS to provide more tailored and meaningful information. This is in line with an emerging field of "computational place modelling" in GIScience (Ostermann et al., 2015; Westerholt et al., 2020). According to Tuan (1977), "place" is more than just a location, and can be described as a location enriched by human experiences. Agnew (2011) proposes three dimensions to define a place, i.e., location, locale, and sense of place.

- Location allows distinguishing a place from other locations in space (either in absolute or relative terms), and thereby answering the question of “where?”. In the above example, the WGS-84 coordinate and the first part of the sentence “*it is located at the front of Atomium, in Brussel, Belgium*” can be considered as information about the location dimension.
- Locale is defined by the (physical) properties of the space, e.g., its boundaries, its components and their spatial configuration, and its affordances (i.e., what the place offers to people there). In the above example, the 2nd part and 3rd part of the sentence can be considered as information about the locale dimension.
- Sense of place is a person’s subjective and emotional attachment to a place. It often arises from personal experience and can vary greatly from person to person. It's about the personal and emotional connections, memories, meanings, and interpretations that individuals associate with a place. In the above example, the last part “it is also where I first met my best friend” can be considered as information about the sense of place dimension.

These three dimensions form a potential framework for semantic enrichment of location. Such semantic enrichment often requires the combination of both qualitative and quantitative spatial data modelling methods, making use of different data sources (Bahrehdar et al., 2019). Research on this aspect is still at an early state, but is very interesting and has a high potential to enable a transition from “location-based services” to “place-based services”(Gao, 2022).

Opportunity 2.3: User modelling and task modelling

Users are a central aspect to be considered for LBS applications. User modelling in LBS aims to represent users, their tasks/goals/purposes of use, and needs, as well as their preferences and constraints (Augstein et al., 2023). Thoroughly understanding and modelling each user and their needs seem to be unrealistic, as users are often very diverse. Clustering the users in terms of their profiles, interests, and behaviors is often needed to simplify the design of LBS. For example, when designing LBS to guide users in a museum, the users might be classified into different groups, e.g., passionate (who need in-depth information on every exhibit), selective (who want detailed information on selected exhibits), and cursory (who move through a gallery and do not have specific target in mind), according to their viewing styles and interests. Based on the user groups, LBS can then adapt their information and services accordingly. For example, for “selective users”, the LBS should be developed to guide them to exhibits that match their interests, while skipping the others. How to effectively classify users based on various data sources (sometimes with very limited information available) for LBS is still an open question (Savino et al., 2021).

Recent years have also seen rapid advances in mobile and wearable (bio)sensors, e.g., mobile eye-trackers, mobile electroencephalography (EEG), functional Near-Infrared Spectroscopy (fNIRS), and galvanic skin response (GSR). Such sensors allow to capture users’ gaze behaviors (e.g., where, when, how long, and in which order certain information in space or about space is looked at) (Kiefer et al., 2017) and physio-psychological status (e.g., heart rate and variability, cognitive workload, motivation, emotional arousal, and brain activities) (Fabrikant, 2023, Qin et al. 2024). Such aspects provide more contextual information about LBS users, which can be used to offer more tailored services and information according to their visual attention and brain activities. Several studies have started to incorporate users’ gaze behavior to enable gaze-based LBS (e.g., to support pedestrian navigation and mobile guide), which provides information according to what a user is looking at (Anagnostopoulos et al., 2017). However, beyond that, the use of gaze behaviors and physio-psychological status in LBS is rarely seen. Many significant research challenges exist, especially regarding processing, decoding, and translating of low-level numeric signal data into high-level physio-psychological status, and the adaptation of the LBS (e.g., the contents and their communication forms) to these gaze behavior and physio-psychological status (together with other contextual information about a user).

As mentioned before, with the rapid advances and the ubiquity of mobile technologies, LBS become integrated parts of people's daily and professional life, leading to many applications. Huang (2022) classified existing applications and tasks LBS support into seven groups: navigation and transportation (e.g., pedestrian/car navigation, car parking, real-time ridesharing, intelligent transport services), infotainment (e.g., information search, mobile guides (e.g., for tourists, shoppers, and museum visitors), location-based social networking, location-based gaming, and location-based learning), emergency and disaster management (e.g., rescue and disaster response), fitness monitoring and healthcare (e.g., exercise and fitness monitoring, remote health monitoring), business (location-based advertisement, location-based billing, usage-based insurance), location-based assistive technology (e.g., for disabled or elderly), and tracking (e.g., fleet/facility management, logistics tracking). This high variety of LBS applications post significant research challenges for the LBS research communities to understand and properly model users' information needs and behaviors when using each of these application types. It is still unclear whether potential common patterns across different application categories exist. Moreover, the application fields of LBS continue to evolve at a fast speed, and many new fields might emerge in the coming years. This will challenge researchers from the LBS domain to explore methods and principles that are still valid and work for future emerging LBS applications.

It is also important to note that information about the mobile user and context (especially his/her tasks or goals) might impact the way how the geo-social environments (See Section 4.1) should be modelled, specifically regarding what aspects and at which level of granularity (in terms of spatial, temporal, and thematic) of the geo-social environments need to be represented in LBS. For example, for an LBS to support car navigation, it might be important to have information about the area the user is moving around, such as the road network, real-time traffic situation, important POIs nearby (e.g., filling stations, landmarks) and weather. Similarly, the tasks or goals of the user might also determine what other aspects of the user and his/her context need to be modelled. For example, an LBS application providing weather information might only need to know the coarse location of the user and ignore other contextual information (like preferences and social situation), while a shopping guide might need details regarding the user's real-time location (at least at the level of a shop), his/her preferences and interests, the available shopping time, and budget.

4.3 Context-aware adaptation

After modelling the geo-social environment and the user and his/her personal context, LBS need to use such information to adapt the services and information accordingly to meet the user's information needs. This process is often called *context-aware adaptation*. During the context-aware adaptation process, computational methods should be developed to identify the "relevant information" to be communicated to the user. Meanwhile, given that various presentation forms of communicating the same information might be possible, methods should be also developed to identify the "best communication form". In summary, the overall research challenge here is: *How can relevant* *information and its most suitable communication form be identified to meet the user's information needs in their context?*

Opportunity 3.1: Conceptualizing and modelling relevance in LBS

Relevance is a central concept in LBS. According to Schamber et al. (1990), it is a term with a multidimensional, dynamic, and complex nature. In general sense, relevance refers to the degree to which something is connected, applicable, or significant to a given matter or context. There is no common agreement on how relevance should be defined and modelled. In LBS, several initial studies have tried to investigate this issue, and they define the term geographic relevance as "a relation between a geographic information need and the spatio-temporal expression of the geographic information objects needed to satisfy it" (Raper, 2007, p. 836; Reichenbacher & De Sabbata, 2011). However, this definition mainly focuses on the perspective of information/data retrieval. A comprehensive investigation of relevance from both information retrieval and information communication (e.g., cartography) perspectives is needed, given that LBS not only need to identify "what relevant information is", but also "how the relevant information should be communicated (e.g., in which communication form)". The nature, characteristics, and components of relevance in LBS, as well as how relevance is linking the geo-social environment and the user, should be also clarified. To address this issue, it might make sense to start from the key components of relevance proposed by many studies in information retrieval (Saracevic, 2007). Some of the prominent ones include: topicality (referring to whether the content or a piece of information directly relates to the subject of a query or task), utility (referring to whether the information is useful or valuable in a given context), novelty (referring to whether the information provides new knowledge or insights), personalization (referring to whether the information aligns with a user's interests or preferences), and understandability (referring to whether the user can comprehend the information, or whether the information matches with the user's cognitive constricts or status). Furthermore, computational metrics and methods to formally represent and assess relevance need to be developed to make the concept operable in the development of LBS applications.

Opportunity 3.2: Techniques of context-aware adaptation

Context-aware adaptation is the process of changing the content, behavior, and/or appearance of an application or service according to the user's context. As identified in Brusilovsky (1996) and further introduced in Huang et al. (2018), the process of context-aware adaptation in LBS needs to consider the aspects of What ("which features of LBS can be adapted?"), When ("When should the adaptation process happen?"), and How ("which techniques are needed to make the adaptation?"). Research on these aspects is emerging in recent years. However, significant research challenges remain, given that answers to such questions are often application-dependent.

In terms of the "How?" (i.e., techniques of context-aware adaptation), several general techniques have been proposed in related research fields (e.g., information retrieval and recommender systems) (Grifoni et al., 2018b): similarity-based reasoning, collaborative filtering, machine learning, and rule-based reasoning. These techniques need to be extended to meet the specific requirements of LBS, e.g., by considering the characteristics and constraints established by space and time. Various computational methods in geography, especially GIScience and cartography, should be integrated. A significant example is time geography, which provides a framework for modelling and visualizing spatial and temporal processes, events, and activities. Furthermore, findings from other research domains, such as spatial cognition and ergonomics (e.g., human factors), should be also integrated.

In many cases, information about the user might be very limited and incomplete due to either a lack of information or privacy-concerns. Computational methods should be developed to still identify relevant information for the user, despite such limitations.

Opportunity 3.3: Level of automation in the context-aware adaptation process

The adaptation process of the services/contents according to the context information can be characterized by various degrees of automation. Two extremes exist (Schou, 2008): self-adaptation (i.e., the system adapts the services automatically without any user interaction), and controlled adaptation (i.e., the user needs to initiate the process). The advantage of the latter is that the user is in control with the system and thus she/he has a high autonomy, while its disadvantage is that the user must do some additional work, which sometimes might not be feasible (e.g., when the user is busy with other tasks like driving). In contrast, self-adaptation has the advantage of “little or (no) effort by the user”, while users might feel “loss of control” of the systems, or even worse they might feel being controlled by the system. The level of automation that is appropriate depends on many factors, including the preferences of the user, the nature of the task/activity the LBS is supporting, the context of usage, the potential consequences of errors or failures, etc. Balancing the benefits of automation, such as increased efficiency and reduced workload, with the need for human oversight, control, and autonomy is an essential challenge in LBS research.

Opportunity 3.4: Optimized distribution of data and processing among the mobile device and the cloud

As can be seen above, the context-aware adaptation process leverages data about the geo-social environment, the user, and her/her context. This raises issues regarding: Where should these data be stored, on the mobile device, or on the cloud? and Where should the adaptation process be executed? Answering to these questions will need to consider not only about technical issues (e.g., the amount of the data, the properties and capabilities of the mobile device, and network conditions), but also non-technical ones, such as data ownerships and privacy. This later issue becomes more important given that many data used in the adaptation process consists of the user’s personal information or travel histories. In the context of contact-tracing app for combatting COVID-19 (Roche, 2020), a similar debate over centralized versus decentralized approaches also illustrates the complexity of this issue. Given that centralized and decentralized approaches seem to have both advantages and weaknesses in LBS applications, computational methods should be developed to help developers identify an optional distribution of data and processing among users’ mobile devices and the cloud.

4.4 Ethical data modelling and processing

LBS provide relevant information to users by modelling the geo-social environments and the users, as mentioned in the previous sub-sections. Such information, especially the latter types, might be private and very sensitive. Some of them can be even considered as personal identifiable information (PII). Therefore, privacy concerns are often raised with LBS. Meanwhile, the increasing use of LBS and location-tracking devices in general public’s daily lives, other social and ethical issues also appear. These aspects need to be carefully considered during the development of LBS and pose many research challenges to various research fields in LBS. The overall research challenge in this direction includes: *How can user's (geo)privacy be preserved during data modelling and processing? How can ethics-aware computational methods be developed in LBS?* Sufficiently addressing these aspects can also help to improve the perceived trustworthiness of the offered location-based information (especially in the era of fake news and generative artificial intelligence GenAI), and increase user acceptances of the LBS application.

Opportunity 4.1: Privacy and ethical issues in LBS

Information privacy concerns the collection and processing of personal data, and is "the claim of individuals, groups, institutions to determine themselves when, how, and to what extent information about them is communicated to others" (Duckham & Kulik, 2006; Westin, 1967, p. 7). Preserving privacy has been a long-standing challenge for LBS (Aloui et al., 2022). LBS concern both the general type of information privacy (i.e., non-location-related, e.g., information about users' preferences, tasks, and personal information) and location privacy (also known as geoprivacy, a specific type of information privacy, e.g., user's current location and location histories). The latter refers to "the ability of an individual to move in public [and private] spaces with a reasonable expectation that their location will not be systematically and secretly recorded for later use by a third party" (Kerski, 2016). Keßler & McKenzie (2018, p. 10) argued that "location can be inferred from non-explicit geospatial information, such as interests, activities, and social-demographics". For example, knowing the type of place (e.g., a Chinese restaurant) someone is visiting in small town in a Swiss Alps skiing area can significantly increase the abilities to identify their spatial location. While research on privacy and LBS are emerging in recent years (Aloui et al., 2022; Elwood & Leszczynski, 2011; Keßler & McKenzie, 2018; N et al., 2021) , systematic studies considering both non-location-related privacy and geoprivacy, as well as both explicit and implicit privacy issues, in LBS are still lacking. Furthermore, potential cases or scenarios where such personal information can be abused should be also documented (Robinson, 2019). Addressing these two topics poses significant research challenges, given that an individual's level of (geo)privacy is difficult to be reliably assessed because it is impossible to know what auxiliary information a third party may have access to (Keßler & McKenzie, 2018).

Recent years have seen more and more people using LBS in their everyday life, e.g., to facilitate their various spatial behaviors at different environments. LBS are becoming an integral part of our daily lives. This also brings other social and ethical issues, both at the individual and society levels. Montello (2009, p. 1835) suggested that "technology change how we think, often by reducing our ability to reason effectively without the technology", which seems to be the case for mobile navigation systems (which are shown to harm our spatial knowledge acquisition and spatial abilities). Therefore, there is a strong need to systematically study the potential side effects of over-reliance on LBS, covering both short-term and long-term effects, as also suggested in Huang et al. (2018). This requires interdisciplinary and longitudinal research efforts. Meanwhile, the impact and implications of LBS on the impartiality, fairness and justice of individual users, the society, and the environments should be also investigated.

Opportunity 4.2: Modelling the trade-off between service quality and (geo)privacy

Obviously, different LBS applications might require different amount and level of granularity of personal data. For example, an LBS application providing weather information for a user might not need to know their exact GPS coordinates, and the city where the user is in is already sufficient to provide decent services. Similarly, a restaurant recommendation LBS might only need to know the user's general vicinity. While more information and finer-grained personal data might enable LBS applications to provide better services (i.e., more relevant results), the service quality being improved is generally not in proportion to the amount and granularity of the data. This challenges the research community to model the trade-off between offering a personalized, efficient service and respecting the (geo)privacy of the individual for different LBS applications. Guidelines regarding the (minimal) amount of personal data, their types, and their level of granularity required for ensuring the usability of various types of LBS applications should be developed. These guidelines should aim to support LBS developers to collect not more data than what is absolutely necessary for the service to function effectively. This concept, known as data minimization, is an essential principle for many privacy laws and can help mitigate privacy risks.

Opportunity 4.3: Techniques of privacy-preserving data modelling and processing

The privacy by design framework calls for privacy to be taken into account throughout the whole system development process (Ann Cavoukian, 2011), offering several foundational principles for system developers, including: (1) Proactive not reactive, preventive not remedial; (2) Privacy as the default setting; (3) Privacy embedded into design; (4) Full functionality – positive-sum, not zero-sum; (5) End-to-end security – full lifecycle protection; (6) Visibility and transparency – keep it open; (7) Respect for user privacy – keep it user-centric. Aiming for general applications, these principles are designed without considering the specific requirements of LBS, which need to consider both conventional information privacy and location privacy. Research that customizes these principles for LBS development should be done. Meanwhile, best practices and recommendations might be also provided to enable transparency and user control in LBS, helping LBS to clearly inform users about what data is being collected, how it is used, and providing them with user-friendly interfaces to control their data.

In addition, computational methods should be also developed and introduced to enable privacy-preserving data modelling and processing in LBS. Several methods have been proposed in relevant disciplines, including pseudonymity, k-anonymity, location obfuscation, and differential privacy (Georgiadou et al., 2020; Keßler & McKenzie, 2018). In recent years, major mobile operating systems, e.g., Apple's iOS, also start to allow the user to control how, when, and at which accuracy level (e.g., precise vs. coarse) her phone shares her location with an app. However, these different methods are suitable for different types of data and there is none one that prevents all types of re-identificaiton or attacks. As mentioned in the previous sections, LBS need to model different types of personal data, including non-spatial personal data (e.g., data about users' preferences, tasks, and personal information) and spatial data (e.g., user's current location and location histories). In terms of the later type, we can further differentiate among discrete location data, discrete location data with additional attribute information, spatial trajectory data (e.g., location histories, containing a series of locations and their timestamps), and spatial trajectory data with additional attribute information (Georgiadou et al., 2020). It is obvious that such different types of personal data in LBS should be treated differently. This challenges the LBS research community to define and offer (improved or new) privacy-preserving computational methods for modelling and processing such personal data in LBS, with the aims to maximizing the quality of the services offered, while minimizing the chance of re-identificaiton of individual users.

Opportunity 4.4: Governance and regulation on privacy-preserving data processing

In recent years, legal frameworks and regulations (e.g., General Data Protection Regulation GDPR in Europe) are being introduced to protect end users' privacy. This challenges the LBS research community to provide best practices or case studies to illustrate how privacy law-compliant LBS can be developed. Such best practices should cover both data modelling/processing (e.g., considering the data minimization principles mentioned in Opportunity 4.2) and user informing (e.g., providing user-friendly interfaces to inform end users about the usage of their data, as well as to allow them to control the use of their data). In addition, Keßler & McKenzie (2018, p. 14) pointed out a dilemma of (geo)privacy regarding the links between these legal frameworks and apps: "Users often have no way of checking whether the location-aware services and devices they use act within the legal and ethical frameworks and adhere to the provided description and privacy policy". While a higher level of user education and societal awareness in the area of (geo)privacy is needed to address this dilemma, methods to identify violations and mechanism to validate privacy-preserving data processing should be also developed. Brokering techniques or other intermediary control mechanism might be developed.

4.5 LBS in large-scale virtual worlds

In recent years, large scale virtual worlds such as massive multiplayer online games or interactive 3D virtual worlds have gained great popularity, especially among the younger generation. Such virtual worlds, e.g., SecondLife, allow people to create an avatar for themselves and have a "second life" in the virtual environment. With the massive and ever-increasing amount of content available, virtual world users typically face the difficulties of finding relevant and exciting content (Marinho et al., 2015), and require some forms of virtual location based services to facilitate their various spatial behaviors of their "second life" in the virtual worlds (e.g., navigating to desired virtual locations, interacting with the virtual environment in a meaningful way). Therefore, it can be expected that future LBS applications will be expanded to both physical and virtual environments. This is a completely new research area. It challenges researchers to define and offer (improved or new) principles, methods, and techniques that can enable LBS to be used in virtual worlds. We believe that many key challenges mentioned above are still applicable to such virtual LBS applications.

5. Conclusions

In this article, we first described "what is special about location-based services?", compared to conventional geographic information systems (GIS) and web mapping applications. These distinct characteristics are mainly on the aspects of "users and tasks", "dynamic and mobile", and "context-awareness". Addressing these unique characteristics, we then presented 4 main key and open research challenges related to context modelling and processing in LBS, and highlighted a list of essential research topics that can be pursued to overcome the challenges (Table 1). These 4 main key challenges cover issues related to "modelling of the geo-social environment", "modelling of the mobile user", "context-aware adaptation", and "privacy-preserving and ethics-aware data modelling and processing". They comprehensively address the notion of context in LBS, with regards to its scientific (e.g., "what does context in LBS contain?" and its roles in LBS; Section 3), technological (e.g., "how can context be computationally modelled and inferred from a variety of data sources?" and "how can it be used to derive relevant information?"; Section 4), and social dimensions ((geo)privacy, the ethical implication of context-aware LBS on individuals and society; Section 4.4).

Table 1. Research challenges and opportunities regarding context modelling and processing in LBS

Open research challenges	Research opportunities addressing each challenge
Modelling of the geo-social environment	• Indoor/outdoor seamless spatial modelling (high definition and 3D) • Social sensing
Modelling of the mobile user	• Ubiquitous positioning • Semantic enrichment of location • User modelling and task modelling
Context-aware adaptation	• Conceptualizing and modelling relevance in LBS • Techniques of context-aware adaptation • Level of automation in the context-aware adaptation process • Optimized distribution of data and processing among the mobile device and the cloud
Ethical data modelling and processing	• Privacy and ethical issues in LBS • Modelling the trade-off between service quality and (geo)privacy • Techniques of privacy-preserving data modelling and processing • Governance and regulation on privacy-preserving data processing

As can be seen in Table 1, many of these challenges and opportunities often present interdisciplinary characteristics, and therefore, require cross-disciplinary efforts. We hope that the research agenda presented in this paper motivates the LBS research community and beyond to join forces to enable the 4A vision (“anytime”, “anywhere”, “for anyone” and “anything” services) and fulfil the 5R (providing “right” information, in the “right” way, at the “right” time, in the “right” place, to the “right” person) requirements of LBS. By doing so, we can best support users’ various spatial behaviors in both physical and virtual worlds, thus propelling LBS towards a future of greater ubiquity and relevancy.

While we believe that this list covers the most essential and fundamental open questions with regards to context modelling and processing in LBS, it is not meant to be exclusive. Meanwhile, the content of the research agenda represents a snapshot in time and might change over time with the new technological and methodological evolvements, such as the development of generative artificial intelligence (GenAI) and multimodal foundation models. We expect that the advances of GenAI and foundation models might help to address some of the above challenges, and might bring some new challenges, such as the trustworthiness of the location-based information provided by AI-backed LBS.

Acknowledgement

This research was partially supported by the Special Research Grant (BOF) at Ghent University [No. BOF/STA/201909/036] and the National Natural Science Foundation of China [NSFC, Grant No. 42230103]. We also thank the editor and three anonymous reviewers for their constructive comments.

References

Abid, M., & Lefebvre, G. (2021). Improving indoor geomagnetic field fingerprinting using recurrence plot-based convolutional neural networks. *Journal of Location Based Services*, *15*(1), 61–87. https://doi.org/10.1080/17489725.2020.1856428

Afyouni, I., Ray, C., & Claramunt, C. (2017). Representation: Indoor Spaces. In *International Encyclopedia of Geography: People, the Earth, Environment and Technology* (pp. 1–12). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.WBIEG0900

Agnew, J. (2011). Space and place. In *The SAGE handbook of geographical knowledge* (pp. 316–330). SAGE Publications Ltd.

Aloui, A., Kazar, O., Bourekkache, S., & Chikh, A. (2022). Protecting user privacy in location-based services over road networks. *Journal of Location Based Services*, *16*(2), 77–118. https://doi.org/10.1080/17489725.2022.2041213

Anagnostopoulos, V., Havlena, M., Kiefer, P., Giannopoulos, I., Schindler, K., & Raubal, M. (2017). Gaze-Informed location-based services. *International Journal of Geographical Information Science* , *31*(9), 1770–1797. https://doi.org/10.1080/13658816.2017.1334896

Ann Cavoukian. (2011). *Privacy by Design in Law, Policy and Practice: A White Paper for Regulators ... - Ann Cavoukian - Google Books*. Information and Privacy Commissioner of Ontario, Canada, 2011.

Augstein, M., Herder, E., & Wörndl, W. (2023). *Personalized human-computer interaction*. Walter de Gruyter GmbH & Co KG.

Bahrehdar, A. R., Koblet, O., & Purves, R. S. (2019). Approaching location-based services from a place-based perspective: from data to services? *Journal of Location Based Services* , *13*(2), 73–93. https://doi.org/10.1080/17489725.2018.1564383

Brusilovsky, P. (1996). Methods and techniques of adaptive hypermedia. *User Modeling and User-Adapted Interaction 1996 6:2*, *6*(2), 87–129. https://doi.org/10.1007/BF00143964

Cao, J., Lam, K. Y., Lee, L. H., Liu, X., Hui, P., & Su, X. (2023). Mobile Augmented Reality: User Interfaces, Frameworks, and Intelligence. *ACM Computing Surveys*, *55*(9), 189. https://doi.org/10.1145/3557999

Chen, R., Li, Z., Ye, F., Guo, G., Xu, S., Qian, L., Liu, Z., & Huang, L. (2021). Precise Indoor Positioning Based on Acoustic Ranging in Smartphone. *IEEE Transactions on Instrumentation and Measurement*, *70*. https://doi.org/10.1109/TIM.2021.3082269

Dey, A. K. (2001). Understanding and Using Context. *Personal and Ubiquitous Computing 2001 5:1*, *5*(1), 4–7. https://doi.org/10.1007/S007790170019

Dreyer, J., Heitmann, S., Erdmann, F., Bauer, G., & Kray, C. (2022). 'Informed' consent in popular location based services and digital sovereignty. *Journal of Location Based Services* , *16*(4), 312–342. https://doi.org/10.1080/17489725.2021.2017495

Duckham, M., & Kulik, L. (2006). Location privacy and location-aware computing. In *Dynamic and mobile GIS: Investigating change in space and time* (pp. 34–51). CRC Press.

Egenhofer, M. J., & Mark, D. M. (1995). Naive Geography. In *COSIT 1995: Spatial Information Theory A Theoretical Basis for GIS* (pp. 1–15). Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-60392-1_1

Elwood, S., & Leszczynski, A. (2011). Privacy, reconsidered: New representations, data practices, and the geoweb. *Geoforum*, *42*(1), 6–15. https://doi.org/10.1016/J.GEOFORUM.2010.08.003

Fabrikant, S. (2023). Neuroadaptive LBS: towards human-, context-, and task-adaptive mobile geographic information displays to support spatial learning for pedestrian navigation. *Journal of Location Based Services*, *17*(4), 340–354. https://doi.org/10.1080/17489725.2023.2258100

Gao, S. (2022). Towards Place-Based GIS. In *New Thinking in GIScience* (pp. 51–58). Springer, Singapore. https://doi.org/10.1007/978-981-19-3816-0_6

Georgiadou, Y., Kounadi, O., & By, R. A. de. (2020). Digital Earth Ethics. *Manual of Digital Earth*, 785–810. https://doi.org/10.1007/978-981-32-9915-3_25

Griffin, A. L., White, T., Fish, C., Tomio, B., Huang, H., Sluter, C. R., Bravo, J. V. M., Fabrikant, S. I., Bleisch, S., Yamada, M., & Picanço, P. (2017). Designing across map use contexts: a research agenda. *International Journal of Cartography*, *3*(sup1), 90–114. https://doi.org/10.1080/23729333.2017.1315988

Grifoni, P., D'Ulizia, A., & Ferri, F. (2018a). Context-Awareness in Location Based Services in the Big Data Era. In *Mobile Big Data* (pp. 85–127). Springer, Cham. https://doi.org/10.1007/978-3-319-67925-9_5

Grifoni, P., D'Ulizia, A., & Ferri, F. (2018b). Context-Awareness in Location Based Services in the Big Data Era. In *Mobile Big Data* (pp. 85–127). Springer, Cham. https://doi.org/10.1007/978-3-319-67925-9_5

Guan, F., Fang, Z., Zhang, X., Zhong, H., Zhang, J., & Huang, H. (2023). Using street-view panoramas to model the decision-making complexity of road intersections based on the passing branches during navigation. *Computers, Environment and Urban Systems*, *103*, 101975. https://doi.org/10.1016/J.COMPENVURBSYS.2023.101975

Gupta, R., Pandey, G., Chaudhary, P., & Pal, S. K. (2021). Technological and analytical review of contact tracing apps for COVID-19 management. *Https://Doi.Org/10.1080/17489725.2021.1899319*, *15*(3), 198–237. https://doi.org/10.1080/17489725.2021.1899319

Huang, H. (2022). Location-Based Services. In W. Kresse & D. M. Danko (Eds.), *Springer Handbook of Geographic Information*. Springer. https://doi.org/10.1007/978-3-030-53124-9

Huang, H., Gartner, G., Krisp, J. M., Raubal, M., & Van de Weghe, N. (2018). Location based services: ongoing evolution and research agenda. *J Locat Based Serv*, *12*(2), 63–93.

Huang, H., Schmidt, M., & Gartner, G. (2012). Spatial knowledge acquisition with mobile maps, augmented reality and voice in the context of GPS-based pedestrian navigation: Results from a field test. *Cartogr Geogr Inf Sci*, *39*(2), 107–116. https://doi.org/10.1559/15230406392107

Huang, H., Yao, X. A., Krisp, J. M., & Jiang, B. (2021). Analytics of location-based big data for smart cities: Opportunities, challenges, and future directions. *Computers, Environment and Urban Systems*, *90*, 101712.

Kerski, J. (2016). Location Privacy. *Geographic Information Science & Technology Body of Knowledge*, *Q3*. https://doi.org/10.22224/GISTBOK/2016.3.2

Keßler, C., & McKenzie, G. (2018). A geoprivacy manifesto. *Transactions in GIS*, *22*(1), 3–19. https://doi.org/10.1111/TGIS.12305

Kiefer, P., Giannopoulos, I., Raubal, M., & Duchowski, A. (2017). Eye tracking for spatial research: Cognition, computation, challenges. *Spatial Cognition and Computation*, *17*(1–2), 1–19. https://doi.org/10.1080/13875868.2016.1254634

Kresse, W., Danko, D., & Fadaie, K. (2022). Standardization. In *Springer Handbook of Geographic Information* (pp. 383–492). Springer, Cham. https://doi.org/10.1007/978-3-030-53125-6_15

Liu, B., Ding, L., & Meng, L. (2021). Spatial knowledge acquisition with virtual semantic landmarks in mixed reality-based indoor navigation. *Cartography and Geographic Information Science*, *48*(4), 305–319. https://doi.org/10.1080/15230406.2021.1908171

Liu, Y., Liu, X., Gao, S., Gong, L., Kang, C., Zhi, Y., Chi, G., & Shi, L. (2015). Social Sensing: A New Approach to Understanding Our Socioeconomic Environments. *Annals of the Association of American Geographers*, *105*(3), 512–530. https://doi.org/10.1080/00045608.2015.1018773

Marinho, L. B., Trattner, C., & Parra, D. (2015). Are Real-World Place Recommender Algorithms Useful in Virtual World Environments? *Proceedings of the 9th ACM Conference on Recommender Systems*, 245–248. https://doi.org/10.1145/2792838

Meng, L. (2022). The "Here and Now" of HD Mapping for Connected Autonomous Driving. In *New Thinking in GIScience* (pp. 329–340). Springer, Singapore. https://doi.org/10.1007/978-981-19-3816-0_35

Min-Allah, N., Alahmed, B. A., Albreek, E. M., Alghamdi, L. S., Alawad, D. A., Alharbi, A. S., Al-Akkas, N., Musleh, D., & Alrashed, S. (2021). A survey of COVID-19 contact-tracing apps. *Computers in Biology and Medicine*, *137*, 104787. https://doi.org/10.1016/J.COMPBIOMED.2021.104787

Montello, D. (2009). Cognitive Research in GIScience: Recent Achievements and Future Prospects. *Geogr. Compass*, *3*(5), 1824–1840.

N, R., Abraham, S., & Das, S. S. (2021). Privacy preserved spatio-temporal trajectory publication of Covid-19 patients. *Journal of Location Based Services*, *16*(1), 25–53. https://doi.org/10.1080/17489725.2021.1906965

Nguyen, K. A., Luo, Z., & Watkins, C. (2020). Epidemic contact tracing with smartphone sensors. *Journal of Location Based Services*, *14*(2), 92–128. https://doi.org/10.1080/17489725.2020.1805521

Ostermann, F. O., Huang, H., Andrienko, G., Andrienko, N., Capineri, C., Farkas, K., & Purves, R. S. (2015). Extracting and Comparing Places using Geo-Social Media. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, II-3/W5*. https://doi.org/10.5194/isprsannals-II-3-W5-311-2015

Perebner, M., Huang, H., & Gartner, G. (2019). Applying user-centred design for smartwatch-based pedestrian navigation system. *Journal of Location Based Services*, *13*(3), 213–237. https://doi.org/10.1080/17489725.2019.1610582

Qin, T., W. Fias, N. Van de Weghe, and H. Huang. 2024. "Recognition of Map Activities Using Eye Tracking and EEG." International Journal of Geographical Information Science. https://doi.org/10.1080/13658816.2024.2309188.

Raper, J. (2007). Geographic relevance. *Journal of Documentation*, *63*(6), 836–852. https://doi.org/10.1108/00220410710836385

Rehrl, K., Groechenig, S., Piribauer, T., Spielhofer, R., & Weissensteiner, P. (2022). Towards a standardized workflow for creating high-definition maps for highly automated shuttles. *Journal of Location Based Services* , *16*(2), 119–151. https://doi.org/10.1080/17489725.2022.2059587

Reichenbacher, T., & De Sabbata, S. (2011). Geographic relevance – different notions of geographies and relevancies. *SIGSPATIAL Special*, *3*(2), 67–70. https://doi.org/10.5167/UZH-51363

Robinson, A. C. (2019). Elements of viral cartography. *Cartography and Geographic Information Science*, *46*(4), 293–310. https://doi.org/10.1080/15230406.2018.1484304

Roche, S. (2020). Smile, you're being traced! Some thoughts about the ethical issues of digital contact tracing applications. *Journal of Location Based Services*, *14*(2), 71–91. https://doi.org/10.1080/17489725.2020.1811409

Saracevic, T. (2007). Relevance: A review of the literature and a framework for thinking on the notion in information science. Part II: nature and manifestations of relevance. *Journal of the American Society for Information Science and Technology*, *58*(13), 1915–1933. https://doi.org/10.1002/ASI.20682

Sarjakoski, L. T., & Nivala, A. M. (2005). Adaptation to context - A way to improve the usability of mobile maps. In *Map-based Mobile Services: Theories, Methods and Implementations* (pp. 107–123). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-26982-7_8

Savino, G. L., Sturdee, M., Rundé, S., Lohmeier, C., Hecht, B., Prandi, C., Nunes, N. J., & Schöning, J. (2021). MapRecorder: analysing real-world usage of mobile map applications. *Behaviour & Information Technology* , *40*(7), 646–662. https://doi.org/10.1080/0144929X.2020.1714733

Schamber, L., Eisenberg, M. B., & Nilan, M. S. (1990). A re-examination of relevance: toward a dynamic, situational definition∗. *Information Processing & Management*, *26*(6), 755–776. https://doi.org/10.1016/0306-4573(90)90050-C

Schou, S. (2008). Context-based service adaptation platform: Improving the user experience towards mobile location services. *2008 International Conference on Information Networking, ICOIN*. https://doi.org/10.1109/ICOIN.2008.4472797

Sun, C. I., Chang, K. S., & Huang, J. T. (2021). Rescue notification system with accurate location estimation for injuries in city Marathons. *Journal of Location Based Services*, *15*(2), 142–168. https://doi.org/10.1080/17489725.2021.1890845

Tuan, Y. (1977). *Space And Place: The Perspective of Experience*. University of Minnesota Press.

Westerholt, R., Mocnik, F. B., & Comber, A. (2020). A place for place: Modelling and analysing platial representations. *Transactions in GIS*, *24*(4), 811–818. https://doi.org/10.1111/TGIS.12647

Westin, A. (1967). *Privacy and freedom*. Atheneum.

Wunderlich, A., Grieger, S., & Gramann, K. (2023). Landmark information included in turn-by-turn instructions induce incidental acquisition of lasting route knowledge. *SCC*, *23*(1), 31–56.

Yao, X. A., Crooks, A., Jiang, B., Krisp, J., Liu, X., & Huang, H. (2023). An overview of urban analytical approaches to combating the Covid-19 pandemic. *Https://Doi.Org/10.1177/23998083231174748*, 239980832311747. https://doi.org/10.1177/23998083231174748

Zahtila, M., & Burghardt, D. (2022). Location-based mobile learning on relief mapping methods. *Journal of Location Based Services* , *16*(3), 153–180. https://doi.org/10.1080/17489725.2022.2072963

Zhou, Z., Weibel, R., Richter, K. F., & Huang, H. (2022). HiVG: A hierarchical indoor visibility-based graph for navigation guidance in multi-storey buildings. *Computers, Environment and Urban Systems*, *93*, 101751. https://doi.org/10.1016/J.COMPENVURBSYS.2021.101751