What is Digital Day Reconstruction?

The Story & Science of Daynamica

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Do you remember what you did yesterday? Where you went? Who you spoke to? How you felt immediately before and after those activities? If you're like most people, you could likely use your memory to flesh out the activities you completed yesterday in broad strokes – yet much of the nuance would be lost. For example, how you felt immediately after leaving the gym. Whether you were frustrated by the small traffic delay you encountered. If a brief text exchange with a friend brought a smile to your face.

As you've already learned, while these details of individuals' daily activities and experiences may seem trivial, they represent a pivotal area of focus within the broader realm of human behavior studies. By delving into the intricacies of daily life, daily activity, and experience data, researchers across a diverse range of disciplines, including the social sciences, humanities, health sciences, and medical fields, can investigate the complex interplay of factors that govern human actions, emotions, and interactions.

The insights gained from these investigations of daily life are invaluable; they increase our understanding of human behavior and wellbeing, while shedding light on the underlying mechanisms that influence societal norms, cultural practices, and public health. Ultimately, innovations in data and research concerning peoples' daily activities and experiences can lead to advancements in social policy, healthcare, medicine, and beyond – thereby improving quality of life on both an individual and collective level.

As methodologies for collecting daily activity and experience data have evolved, there's been a significant innovation: the Day Reconstruction Method (DRM). Developed to overcome the limitations of traditional recall surveys, DRM asks participants to systematically reconstruct the previous day's activities and experiences. This approach has two key benefits. First, it enhances the accuracy of self-reported data. Second, it allows for a more comprehensive collection of information about how individuals allocate their daily time, as well as the emotional experiences associated with each of their daily activities. With DRM, researchers can access more detailed and nuanced insights into peoples' daily lives, significantly deepening our comprehension of human behavior and experiences within everyday contexts.

In this book, we explore the advancement of the traditional DRM to *Digital Day Reconstruction* (DDR) – a technique inspired by the traditional DRM and enhanced through the incorporation of smartphone technology. The core innovation of DDR, facilitated by smartphones, is the combination of both objective mobile sensing and subjective human input to gather digital, real-time data about an individual's activities and experiences over the course of a day. This modern approach offers clear advantages over the conventional DRM, including the use of recursive machine learning and GPS-based data collection to reduce respondent burden, improved data accuracy and comprehensiveness, simplified data management, and streamlined post-processing capabilities.

In this chapter, I'll take you through the decade-long journey of co-inventing the Daynamica app with my collaborators. Next, I'll reveal what makes DDR different and more advantageous than other activity data collection techniques. Finally, I'll examine the challenges and ethical considerations of applying DDR in human subject research.

The Journey to Digital Day Reconstruction

The Story Begins

The journey to Digital Day Reconstruction (DDR) begins with my doctoral research in Urban and Regional Planning at the University of North Carolina at Chapel Hill in 2007. My dissertation, "The Built Environment, Activity Space, and Time Allocation", examined the impact of urban environmental factors such as population density, land use mix, and walkability on individuals' daily activities patterns in space and time. The data for my study was gathered through a telephone survey method known as computer-assisted telephonic interviews (CATI), in which participants reported their daily activities from the previous day; this information was then manually transcribed into digital format by the researchers. While useful, this method is time-consuming, labor intensive, and can introduce biases due to the nature of self-reporting.

During this time, the technological landscape was undergoing a significant transformation with the widespread integration of GPS technology into consumer smartphones. Apple introduced the iPhone (which featured built-in GPS capabilities) on January 9, 2007, marking a critical turning point in the ubiquitous adoption of GPS-enabled mobile devices. After the launch of the iPhone, the development of GPS technology in smartphones underwent a rapid and significant evolution, marked by considerable improvements in chip design and power efficiency. Additionally, the emergence of new satellite systems like the European Union's Galileo and China's BeiDou provided valuable alternatives and complements to earlier systems (including the US-developed NAVSTAR GPS and Russia's GLONASS), significantly improving the accuracy of GPS technology for users worldwide. Collectively, these advancements propelled the capabilities of GPS in mobile devices to new heights.

The rise of mobile sensing technology, together with smartphones' increased computing power and interactive capabilities, laid a solid foundation for the practical realization and implementation of the DDR concept. In this new technological landscape, I recognized that leveraging smartphone technology for capturing spatiotemporal data on people's daily activities would be a natural fit; the movements tracked by a smartphone could serve as an accurate proxy for the spatial and temporal patterns of the user's daily activities. Following my appointment as an assistant professor at the University of Minnesota in 2008, I was motivated by the rapid integration of GPS technology into consumer smartphones to seek collaborations and funding for developing smartphone applications aimed at capturing individuals' daily activity data in digital formats.

The development of the smartphone-based DDR technology was truly a collaborative effort. Between 2011 and 2018, with the support of multiple government-sponsored grants, I worked with various collaborators to develop and continually improve versions of an application that would collect digital data on individuals' daily activities and experiences. This app – initially known as UbiActive, later named SmarTrAC, and eventually branded as Daynamica – underwent several evolutions in both naming and functionality to better meet the needs of our sponsors and users, and to reflect DDR's objective more precisely.

UbiActive

UbiActive, the first iteration of our DDR app, was funded through a 2011 development grant from the Intelligent Transportation Systems (ITS) Institute, a federally funded University Transportation Center headquartered at the University of Minnesota (operational from 1991 until 2013). The sponsored project was titled "Smartphone-Based Travel Experience Sampling and Behavior Intervention among Young Adults". Driven by the need to align the project closely with the interests of the sponsor, the emphasis of UbiActive was on tracking daily trips, rather than daily activities.

The UbiActive project forged a long-term collaborative relationship between me and Dr. Chen-Fu Liao in the University of Minnesota's Department of Mechanical Engineering. Together with two additional collaborators, Frank Douma and Qian Chen, we designed UbiActive to capture daily trip information, administer surveys about travel-related psychological experiences when a completed trip was detected, and provide daily user-summarized information on travel-related physical activity and psychological experiences. Specifically, UbiActive has three key functionalities, including:

- An automatic sensing mechanism that utilizes the smartphone's GPS receiver and built-in accelerometer to collect sensory data on location change, speed, and acceleration.

- An after-trip survey mechanism that processes the sensory outputs and triggers a survey allowing participants to self-report trip information immediately after the completion of a trip.
- An assessment and reporting mechanism that summarizes the sensing and survey outputs and provides a daily user report about the total amount of physically active trips, trips with good psychological experiences, and the total amount of calories consumed by the user's daily travel behavior.

The performance of UbiActive was tested in the lab setting, as well as among a small group of smartphone users who used a wide range of Android phones. Five popular Android phone brands were included in the tests including HTC, LG, Motorola, Samsung, and Google. Results from the tests confirmed UbiActive's ability to collect real-time, second-by-second locational and acceleration data through smartphone sensors, as well as its ability to collect self-reported additional travel behavior data through the automatically triggered after-trip surveys. More information on the UbiActive work can be found in Fan, Chen, Douma, and Liao (2012).

SmarTrAC

The successful development of UbiActive demonstrated that smartphones could automatically identify trips (including their start and end points) in real time using raw sensing data from the built-in GPS receiver and accelerometer. This led to the conceptualization of SmartTrAC – an improved version of the app with enhanced data mining and machine learning capabilities.

The development of SmarTrAC was funded from 2013 to 2015 by the U.S. Department of Transportation Intelligent Transportation Systems Joint Program Office's Dynamic Mobility Application program, under the project titled "SmarTrAC: A Smartphone Solution for Context-Aware Travel and Activity Capturing". For this version of the app, I worked closely with University of Minnesota's Dr. Julian Wolfson in Biostatistics and Dr. Gediminas Adomavicius in Information and Decision Sciences; both are experts in data mining and machine learning techniques.

Figure 1 illustrates the high-level architecture of SmarTrAC broken down into four logical software and data components: the **Sensor Data Capturer**, the **Sensor Data Processer**, the **User Interface**, and the **Main Database**. Among the four major components, the **Sensor Data Processer** presents a major innovation by incorporating three machine-learning modules that enable automatic detection and classification of daily activity and travel episodes:

- The **activity/trip separator module** predicts whether the user is in the trip (travel) mode or activity (dwelling) mode at a current time (or near current, with a small-time delay).

- The **travel mode classifier module** predicts the transportation mode during trip episodes at a current time (or near current, with a small-time delay). The predicted outcome can be any of the following six categories: car, bus, rail, wait, bike, and walk.
- The **activity type predictor module** predicts the activity type of each activity (dwelling) episode after completion of the activity episode. This predictor could also be called trip purpose predictor, as it identifies the trip purpose of each trip episode after completion of the activity episode for which the trip was conducted. The predicted outcome can be any of the following seven categories: home, work, education, shopping, eat out, social/recreation/community, and other personal businesses.

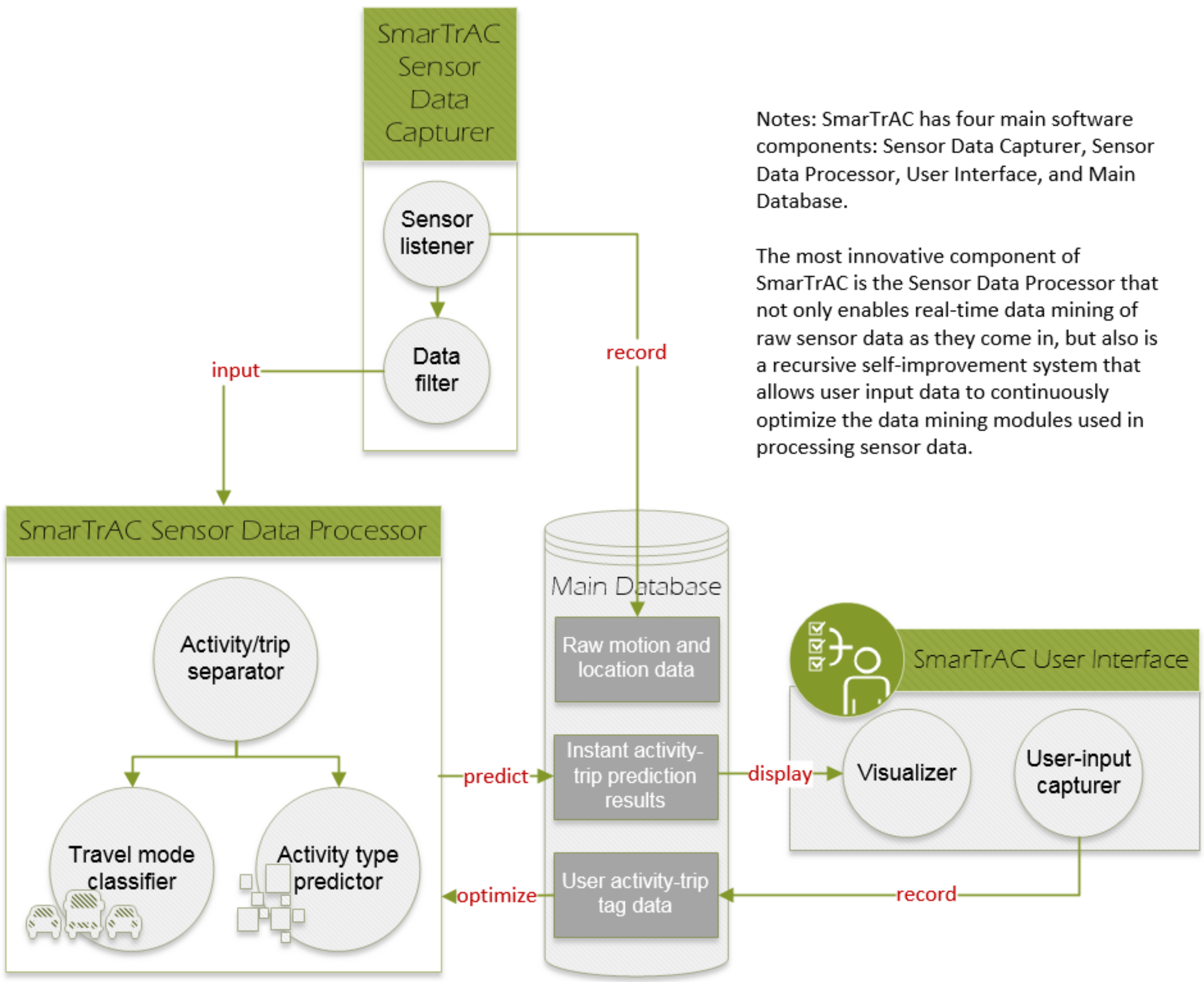


Figure 1. SmarTrAC high-level architecture
Image credit: Yingling Fan

Another key innovation of SmarTrAC was the reciprocal interactions between the machine-learning modules in the **Sensor Data Processor** and the **User Interface** components. Specifically, the **User Interface** visualizes predictions made by the machine-learning algorithms, offering users the opportunity to correct any inaccuracies and contribute additional details. This process of incorporating user feedback for annotation and correction not only enriches the dataset with more detailed information about daily activities and trip, but also fine-tunes the machine-learning algorithms through this human-validated feedback loop.

With its comprehensive focus on capturing both activities and trips throughout the day, SmarTrAC offered a more complete expression of the DDR concept than UbiActive, which was primarily concerned with trip detection. In pitching SmarTrAC to the project sponsor (the U.S. Department of Transportation) we emphasized the interconnectedness between activities and trips; activities are essentially the episodes between trips and trips are essentially the episodes between activities. Consequently, acquiring information on activities will only help our understanding of travel behavior. Our articulation resonated with the sponsor, securing the support needed to fully actualize the DDR concept. As a result, SmarTrAC enabled the systematic and digital reconstruction of daily activity routines (including trips) from smartphone sensing data, offering a comprehensive view of an individual's day.

The performance of SmarTrAC was tested in the lab and in the field through two rounds of seven-day field tests with 17 Android phone users. Field test results suggest that SmarTrAC had a reasonable battery consumption rate, a moderate data storage and transmission requirement, a high accuracy in correctly identifying activity and trip episodes, a high accuracy in correctly classifying the travel modes of each trip episode, and a medium-high accuracy in classifying the types of activity episodes. More information on the SmarTrAC project can be found in Fan, Wolfson, Adomavicius, Das, Khandelwal, and Kang (2015).

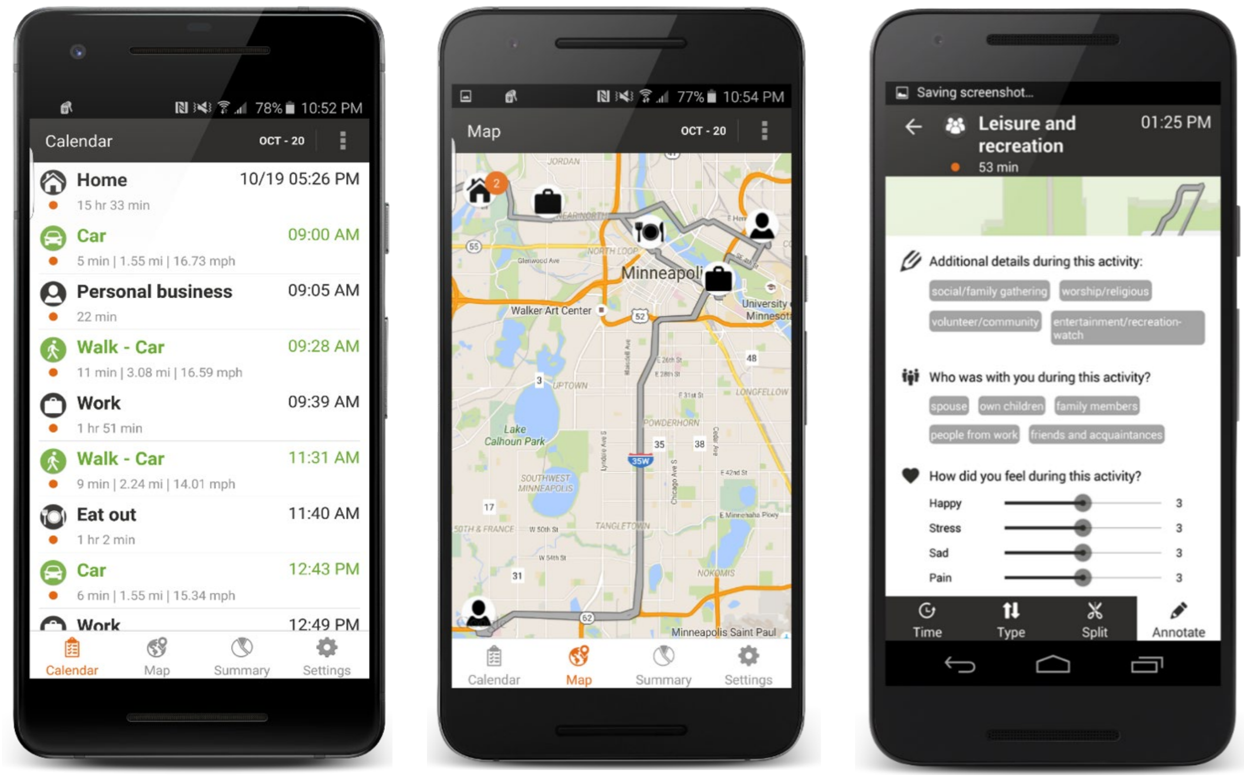
The SmartTrAC project led to peer-reviewed publications, including Martin et al. (2017) and Ermagun et al. (2017). Additionally, the originality and novelty of work were recognized through the awarding of a U.S. patent in 2017, titled "Travel and Activity Capturing" (Fan, Wolfson, Adomavicius, 2017).

Daynamica

The leap from UbiActive to SmarTrAC was characterized by substantial technical advancements, notably through the integration of advanced machine learning and artificial intelligence methods. In contrast, the evolution from SmarTrAC to Daynamica between 2015 and 2018 focused more on gradual improvements, including clarifying the app's objectives and enhancing the core features of DDR. The renaming from SmarTrAC to Daynamica was strategic, aiming to mirror its broader ambition of exploring the intricacies of daily activities and experiences. This change marked a move away from simply tracking activities to a more profound objective of understanding the nuances of everyday life.

App development and refinement between 2015 and 2018 was primarily funded by two government agencies: the United States National Science Foundation (NSF) under the project "SRN: Integrated Urban Infrastructure Solutions for Environmentally Sustainable, Healthy and Livable Cities" and the Twin Cities Metropolitan Council (the Twin Cities region's federally designated metropolitan planning organization) under the project "Smartphone-Based Interventions for Sustainable Travel Behavior: The University of Minnesota Parking Contract Holder Study".

Both the NSF and Metropolitan Council projects extended the app's functionalities. In the NSF project, the Daynamica app was refined to measure emotional wellbeing and happiness of people "in the moment" as they experienced the city. With the support of this grant, the user interface of the app was significantly improved. In addition, the capability of the app was expanded to include a third "M"— momentary emotional assessment (repeated, real-time assessments of human subjects' emotions in their daily life settings)—in addition to mobile sensing and machine learning. Although there were many momentary emotional assessment apps on the market in the 2010s, none of them had offered this function in conjunction with automated day reconstruction, which allows assessed emotions to be examined in the context of daily activities and trips.



Daynamica constructs the activity-trip sequence in real time from mobile sensing data, inferring activity/trip start/end time, activity type and trip mode.

Daynamica captures and displays detailed spatial information of each activity/trip, including activity locations and trip trajectories.

Users can interact with Daynamica to confirm or correct the activity/trip inferences and provide additional details (such as emotional experience) about each activity/trip.

Figure 2. Daynamica Main Interface

Image Credit: Yingling Fan

Figure 2 illustrates the main user interface of the Daynamica app used in the NSF project. As shown in Figure 2, the app displays the temporal and spatial information of the automatically reconstructed activity and trip episodes. It also allows the user to interact with the app at their convenience to provide additional information about the reconstructed activity and trip episodes. In the NSF project, the Daynamica app prompts the respondent to assess the intensity of their momentary emotions during each detected activity and trip episodes, using a scale of 0–6: happy, pain, sad, tired, stressful, and meaningful. These emotional assessment questions were based upon the validated "Subjective Well-Being Module of the American Time Use Survey" (ATUS).

The NSF-funded project allowed us to collect week-long activity details from 372 participants in the Minneapolis-St. Paul metropolitan area, which generated detailed information on a total of 12,877 daily activities and 12,821 daily trips. Figure 3 illustrates how Daynamica collected detailed activity and emotional experience data over seven consecutive days for each participant. The graphical representation includes wider bars segmented by various colors to denote the sequence of activities throughout each day, while narrower green bars vary in shade to depict the fluctuating levels of happiness throughout each day, providing a visual interpretation of both the participants' routines and emotional journeys.

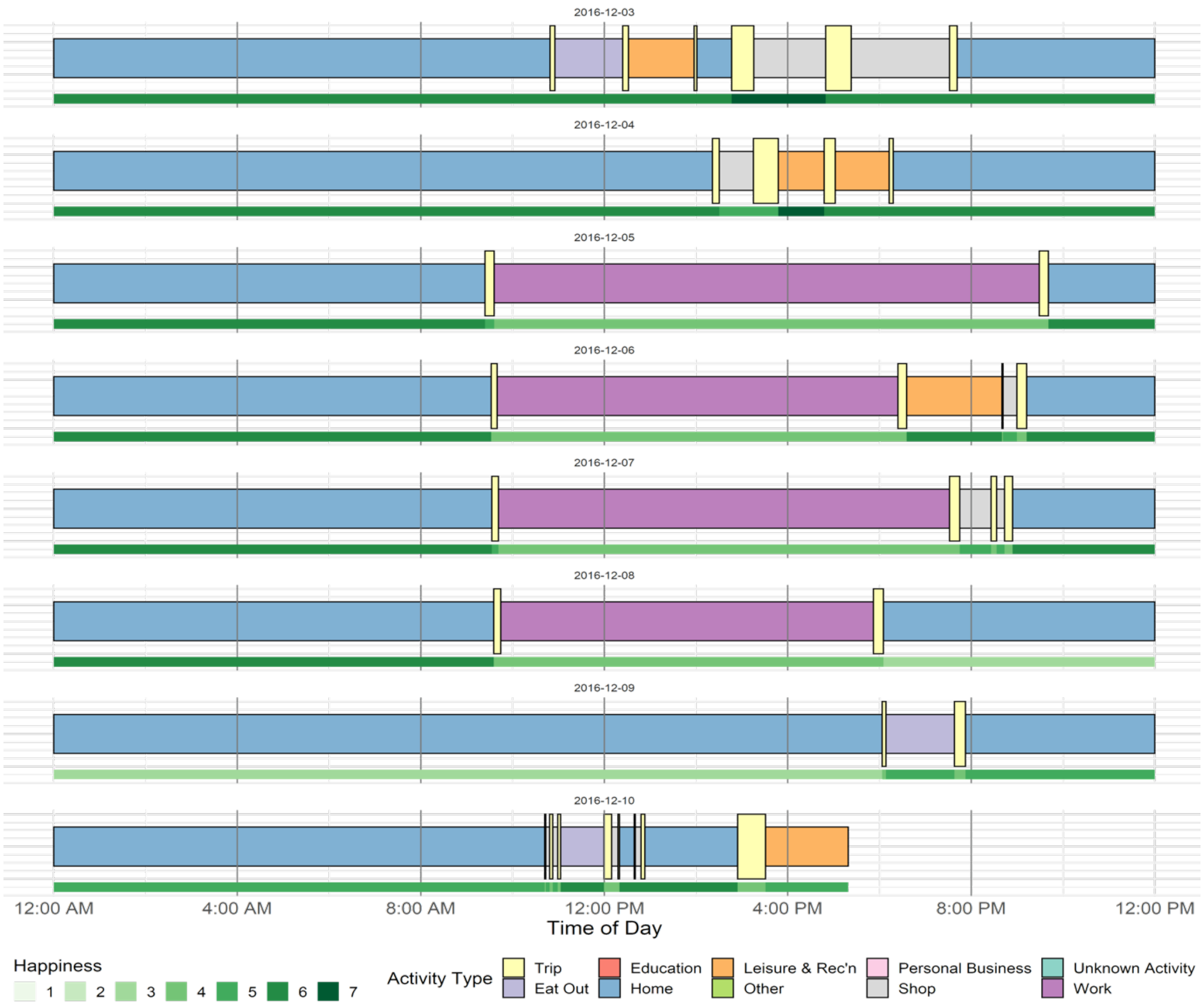


Figure 3. A participant's seven days of activities and happiness levels
Image credit: Andrew Becker

The dataset created through the NSF-funded project was the first of its kind, combining multi-day objective spatiotemporal information from smartphones with real-time, self-reported data on types of activities, experiences, and contexts. This innovative dataset sets a new benchmark in the field distinctively apart from the ATUS data (which also focuses on capturing daily activities and emotional experiences and relies on the traditional DRM approach). In comparison, the ATUS data is much more limited than the Daynamica data because ATUS requires participants to recall and report activities of just a single 24-hour period. Moreover, because of the burdensome effort involved in recalling daily activities, the ATUS "Subjective Well-Being Module" restricts participants to reporting the emotional experiences of only three specific activities and does not provide data on emotional experiences throughout the entire day.

The value and impact of the Daynamica dataset generated by the NSF-funded project are underscored by its utilization in academic research, contributing to five doctoral dissertations (Das, 2020; Wang, 2020; Erinne, 2022; Brown, 2020; Becker, 2022) and over a dozen peer-reviewed publications (Fan et al, 2019; Lal et al, 2020; Ambrose et al, 2020; Wang et al, 2021; Ermagun et al, 2022; Erinne et al, 2022; Ambrose et al, 2023; Tao et al, 2023; Lal et al, 2020; Wu et al 2019). This widespread use not only attests to its innovative approach, but also signifies its potential to revolutionize how daily activities and emotional experiences are studied, offering insights that were previously unattainable with traditional methods.

In addition to the NSF funding, funding from the Twin Cities Metropolitan Council also supported the development and refinement of the Daynamica app. In this project, new functions were added to the Daynamica app to provide carbon footprint information associated with each trip that involves car segments as well as more sustainable travel mode recommendations (e.g., transit, bike, walk) for these car trips. By providing carbon footprint information and the benefits of the suggested alternative modes, along with instructions for how to use the suggested modes, the Daynamica app utilizes the 'awareness, motivation, action' paradigm to educate the public and promote changes and interventions for more sustainable travel behavior. More information about this project can be found in Fan, et al (2020).

Founding Daynamica, Inc.

By 2018, the Daynamica app was market-ready; we obtained a U.S. patent and began to explore commercialization. Although commercialization efforts at public universities may appear to conflict with public benefits as these efforts often mean the privatization of publicly funded technology, on Daynamica's journey to commercialization, I learned this is often not the case.

The University of Minnesota's Office for Technology Commercialization actively encouraged and supported my team in exploring the commercialization of the Daynamica technology. They presented persuasive arguments that commercialization could advance the public interest by bringing valuable innovations to the market more swiftly and efficiently than academic pathways alone would allow. Transitioning technology development to a startup can circumvent bureaucratic challenges, tapping into entrepreneurial funding and flexibility to hasten development. The focus was on acceleration to enhance the societal and economic impact of innovations, ensuring that beneficial technologies are delivered to the market and the public promptly.

In 2018, with the assistance from the University’s Office for Technology Commercialization, I co-founded Daynamica, Inc. with Drs. Julian Wolfson, Guang Yang and Chen-Fu Liao. The company was officially formed as a Delaware C-Corporation on January 23, 2018. After establishing the company, the University of Minnesota awarded Daynamica, Inc. an exclusive worldwide license to deploy the patented “Travel and Activity Capturing” technology for developing DDR apps in return for a ten-percent equity share in the company. In addition, Daynamica, Inc. is also obligated to pay the University a minimum annual royalty fee of $5,000 as long as the licensed U.S. patent remains active (through September 2032).

A memorable part of our entrepreneurial adventure was the creation of our company logo. Mariana Poskus, an urban planning student from the Humphrey School of Public Affairs (my academic home at the University) was responsible for our logo's design. I had always admired Mariana's artistic abilities and design skills during her study at the Humphrey School and hired her to design our company's logo.

We aimed for a logo that represented our app's fundamental idea—illustrating the daily activities of people through time and space. After several iterations, the chosen design (the bottom right corner of Figure 4) resonated with us; it not only mimicked a sundial, echoing our app's aim to organize one's day, but also ingeniously incorporated the shape of the capital letter D. Furthermore, we adjusted the sundial shape to look more like an arrow, indicating direction and movement. During the design process, we amusingly noticed that our logo bore a resemblance to a duck in mid-quack. Consequently, we opted to emphasize the green color over orange to make the logo less duck-like.

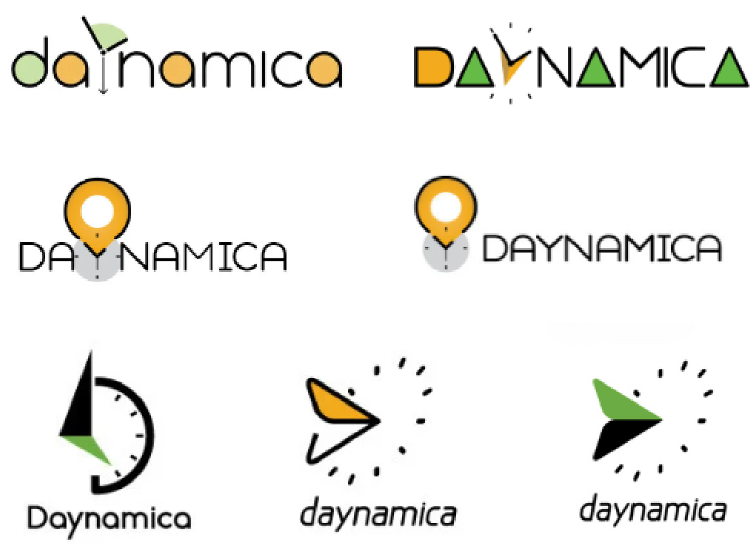


Figure 4. Iterations of Daynamica Logo Design
Credit: Mariana Poskus

Following Daynamica's commercialization, company co-founder Dr. Guang Yang led the development of the app's iOS version. The IOS version became available in the Apple App Store on April 28, 2020. This development marked a significant milestone for the company and provided evidence to the Office of Technology Commercialization's perspective that commercialization facilitates the acceleration of technology development. Prior to commercialization, the app was solely available on Android via the Google Play Store because research funding does not typically cover tasks that lack novelty, including the creation of an iOS version after an Android version is already in place.

The data generated through the Daynamica app is hosted on the cloud. Company co-founder Dr. Chen-Fu Liao oversees the operation of a secure, cloud-based server infrastructure hosted through Amazon Web Services. The database on the server is configured to receive and securely store data transmitted directly from the app. The AWS-hosted environment not only offers robust scalability and reliability, but also maintains integrity and availability of the app's data, ensuring that researchers have continuous and secure access to their Daynamica data.

To further facilitate researchers' instant access to the app-generated data, company co-founder Dr. Julian Wolfson oversees the development of a web-based dashboard designed to aid in study management. This dashboard initiative also benefited from the work of Drs. Roland Brown and Andy Becker, who contributed as temporary contractors for the company following the completion of their doctoral degrees in biostatistics, under Dr. Wolfson's mentorship. The dashboard was developed using R Shiny and serves as a sophisticated tool designed to streamline study management for researchers. This intuitive platform offers a comprehensive suite of features that facilitate the real-time monitoring, analysis and reporting of study data. Key functionalities include interactive data visualization, participant tracking, and customizable analytics options, allowing researchers to easily monitor, manage, and interpret data in real time.

Daynamica's Growth

Marketing & Monetization

To date, the growth of Daynamica, Inc. has been almost entirely organic. Given the technical expertise of its co-founders, marketing is an area outside the team's core strengths. As a result, the company has mostly attracted customers from the co-founders' professional networks. The majority of the company customers have been academic researchers focusing on understanding the 5W's (Who, What, When, Why, and Where) of daily life activities and experiences. These researchers are typically from the social and health sciences domains, and tend to purchase the Daynamica technology to meet specific research project needs. Consequently, the company's income largely stems from project-specific, fixed-price contracts ranging between $10,000 and $40,000. The variation in pricing is attributed to several factors, including:

- Whether the research study requires HIPAA compliance and additional security requirements.
- The number of study participants involved in data collection.
- The length of data collection period.
- The extent of app customization needed for tailoring the front-end mobile system and the back-end online platforms.

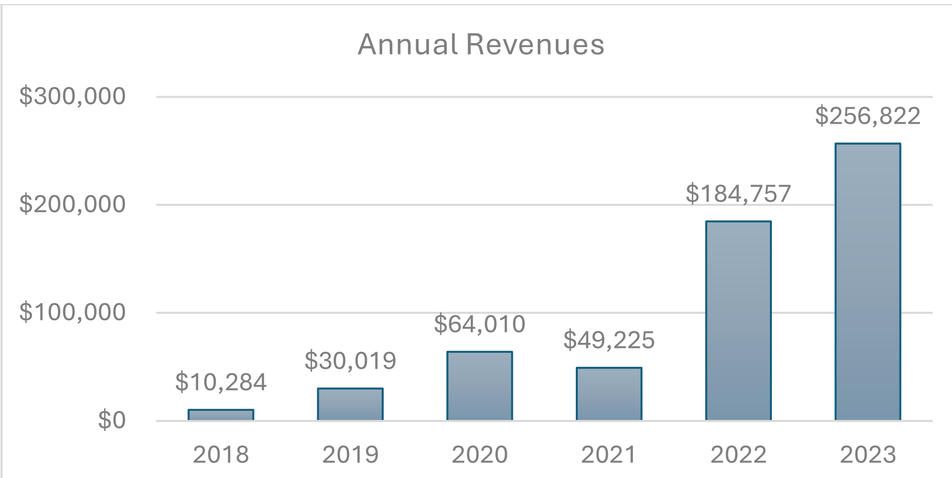


Figure 5. Annual Company Revenue at Daynamica

Despite the lack of marketing efforts, the company has had healthy growth in revenues since its establishment in 2018. Figure 5 illustrates annual growth in company revenues. Since its commercialization, researchers across the U.S. have successfully deployed Daynamica in research studies ranging from urban gardening, transportation, and air quality research in urban planning to health and well-being research in public health. Projects that used Daynamica technology include:

- *Mood State in Transport Environments*
- *Urban Gardening and Emotional Well-Being*
- *Urban Green (Infra)structure for Pedestrian Health*
- *Digital Twin City for Age-friendly Communities: Crowd-biosensing of Environmental Distress for Older Adults*
- *Using smartphone sensor technology to characterize ambulatory patterns of patients with peripheral artery disease receiving supervised exercise training*
- *Fighting Obesity by Reinventing Public Transportation: A Natural Experiment*
- *Implementing Personalized Exercise Prescriptions through Mobile Health in Rural Elderly Cancer Survivors*
- *Advancing Equity in Accessibility and Travel Experiences: The Role of Gender and Identity*

- *Time toxicity of cancer: the time demands of cancer-related activities and their impact on well-being and quality of life*
- *Leveraging mobile monitoring, low-cost sensors, and Google Street View imagery to identify and modify street-level determinants of exposure to particulate air pollution*

Market Research

In addition to project-based contracts, Daynamica's commercialization journey benefited from two federal programs designed to facilitate the commercialization of technological innovations: the National Science Foundation's Innovation Corps (I-Corps) program and the National Institutes of Health (NIH)'s Small Business Technology Transfer (STTR) program. We participated in the 2021 winter cohort of the I-Corps program, conducting 103 customer discovery interviews focusing on two major sectors: clinicians and healthcare providers, and academic researchers who study human behavior.

For the first sector – clinicians and healthcare providers – we hypothesized that they would want to use our tool to improve accuracy and comprehensiveness for human data collection in mobile, everyday life settings. We found that this group doesn't get paid to review data, but wants digestible insights. Plus, a lot of data already exists in the healthcare ecosystem. As a result, it's not about getting more data, it's about getting actionable data that can be integrated into the current workflow. New products must demonstrate value for the customer, such as reduced costs, improved outcomes, a better experience, or increased revenues. Key concerns for this group are privacy, HIPAA compliance, and cost.

For the second sector – academic researchers studying human behavior – we hypothesized they would want accurate and comprehensive data on the contexts and experiences of the studied behavior to make more rigorous discovery of the causes and consequences of these behaviors. We found that these researchers were typically trying to develop breakthrough solutions to problems. For example, researchers developing therapies for physical rehabilitation wanted a more complete picture of out-of-lab physical activity levels and experiences of their participants with continuous measurement and monitoring of physical activity level and experiences. Currently, objective sensing data solutions often leave out important information, and are not flexible enough for these researchers. For this group, HIPAA compliance and total cost are key concerns. Typically, researchers' budget is determined by project scope and funding source, and the data acquisition budget is between 5- and 10-percent of the project's funding.

Emerging Opportunities

We conducted customer discovery interviews with researchers who study daily life behaviors and who were funded by the National Science Foundation, the National Institutes of Health, or both. The interviews provided valuable insights into our prospective customers. The interviews also led to the development of a project with researchers from the Medical School at the University of Minnesota, i.e., customizing the Daynamica technology into a new digital health tool for cancer patients to monitor treatment burden and improve well-being.

For cancer patients, treatment-related logistical burden can lead to decreased well-being across multiple dimensions. Cancer researchers and professionals have coined the term logistic toxicity to describe how the day-to-day logistical burden of carrying out treatment tasks can have toxic effects on patient well-being [4-6]. However, due to the lack of reliable tools to remotely monitor patients' logistical challenges and the associated impacts, logistic toxicity has been largely unaddressed in cancer care delivery. The solution we envisioned was a remote patient monitoring tool that captures treatment burden information on an ongoing basis to empower patients to advocate for care that better fits their life, give providers new insights into potential reasons for treatment nonadherence and nonresponse, and allow health systems to design more patient-centered care regimens.

By building upon the existing Daynamica technology in collaboration with the University of Minnesota (UMN) Masonic Cancer Center, we hope to develop the first digital health app for cancer patients to continuously monitor logistic toxicity in their daily lives. In 2022, our proposal *App-Assisted Day Reconstruction to Reduce Treatment Burden and Logistic Toxicity in Cancer Patients* won the NIH Small Business Technology Transfer (STTR) Phase I grant, producing significant revenue for the company. As shown in Figure X, between 2021 and 2022, the annual revenue more than tripled to reach $184,757 in 2022.

As Daynamica, Inc. continues its growth, the company strives to provide both business-to-business and business-to-customer products for any entities and individuals interested in human behavior and well-being data collection. Given the unmet needs in the medical and healthcare industry for remote patient behavior and well-being monitoring, the medical and healthcare industry is a targeted area for growth for Daynamica, Inc.

Understanding Everyday Life Symposium

Because the DDR-based Daynamica technology offers a new way to decode everyday activities and experiences, it enables researchers from a diverse range of fields to make new discoveries. As a result, the company's leadership saw the need for a cross-disciplinary knowledge exchange focused on its many uses and capabilities. To meet this need, we convened a one-day symposium on July 29, 2022 – *Understanding Everyday Life: Advancing Social and Health Sciences through Digital Day Reconstruction*. The symposium brought more than 70 researchers to the University of Minnesota campus and featured a broad range of research projects that have used the Daynamica technology for the purposes of understanding everyday life, as well as advancing human health and social equity.

Speakers at the symposium represented a wide variety of disciplines, including civil and environmental engineering researchers from Princeton University, gender equity researchers from the Minnesota Population Center, construction science and urban planning researchers from Texas A & M University, geography researchers from the Ohio State University and kinesiology, and cancer care researchers from University of Minnesota. These researchers reported groundbreaking results ranging from the connections between time-use behavior and well-being outcomes to the effects of environmental exposures on well-being disparities.

During the conference, I was both humbled and excited to hear from these researchers how Daynamica has helped generate previously unavailable data that they are using to make scientific discoveries and improve people's lives. Seeing the groundbreaking ways that the technology I envisioned and developed is now being used inspired me to develop this book to provide an even deeper look at the story behind Daynamica, its power, and its possibilities. I understood that through this book, I could communicate the full scope of our technology to an even larger audience, harnessing the potential I saw during that day-long event and increasing it exponentially.

The Science of DDR

Next-Level Day Reconstruction

The traditional recall-based DRM was initially created by well-being researchers to increase the accuracy of recall-based data on daily life experiences. It is suggested that when participants are asked to recall their daily life experiences based on a self-reconstructed sequence of activities throughout the day, they will have more context to elicit specific memories and reduce recall errors. Building upon DRM, DDR offers at least three methodological and technical advancements: automated, real-time activity detection, on-the-fly visualization and annotation, and recursive self-improvement.

DDR's automated, real-time activity detection combines smartphone sensing with advanced statistical and machine learning techniques to automatically detect, identify, and summarize attributes of daily activities. Capitalizing on the smartphone's computing capability, it processes the raw sensor data using rules derived from statistical and machine learning techniques, segments and partitions time series into activity episodes, and summarizes the spatial and temporal attributes of the segmented activity episodes. Compared to the traditional DRM, DDR has a much lower respondent burden because it allows automatic data collection on various activity attributes.

On-the-fly (real-time) visualization and annotation capitalizes on the smartphone's communication capability, as DDR incorporates momentary survey techniques to allow users to view and provide contextual information on the identified activity episodes at their convenience, in real time, or both. It captures many more dimensions of travel behavior data than the existing passive sensing tools that primarily focus on location and route tracking, enabling the collection of more detailed contextual and experiential data on daily activities.

With recursive self-improvement, DDR allows user input data to interact with and optimize its machine-learning modules so that they continuously adapt themselves to the tasks they need to perform, improving prediction models in two important ways. First, user input data can transform the initial "generic" prediction models for travel mode and activity type into "personalized" prediction models. The initial prediction models for DDR are externally trained using labeled training data specifically collected by the researchers. Once DDR is used by the user to collect personal travel and activity data, the collected personal data (sensor data along with user tags) can be used to augment the external training data to update prediction models.

The second way recursive self-improvement functions in DDR is allowing user input data to validate automatically identified activity locations based upon the user's historical activity locations. Each time a user confirms or corrects the predicted activity type with the DDR annotation function, the user input will be used to update a pre-existing table that stores the relationships between locations and activity types. Because the pre-existing tables are designed as a rule-learning component in the activity type predictor module, any updates to the pre-existing table will improve the predictive accuracy of the activity-type predictor module.

Methodological Evolution in Activity Data Collection

The three unique functions of DDR bring together mobile sensing, machine learning, and momentary assessment seamlessly to enable the collection of daily activity and experience data in more advanced ways than previously existing methods. To further illustrate this difference, let's look at the existing methods for capturing daily activities and experiences, and compare them with DDR-based Daynamica technology.

Figure X illustrates the methodological evolution in the field of activity data collection. The earliest daily activity data-collection method is paper- or phone-based recall survey, which is prone to recall bias. Researchers later developed the diary survey approach with the intention to reduce recall bias. More recently, technological advances, such as mobile devices, Global Positioning Systems (GPS) and smartphones, have energized the use of GPS to record location changes and travel routes and to collect self-reported data – enabling the collection of both sensor data and user input data (in either real-time or at the user's convenience) in one single device.

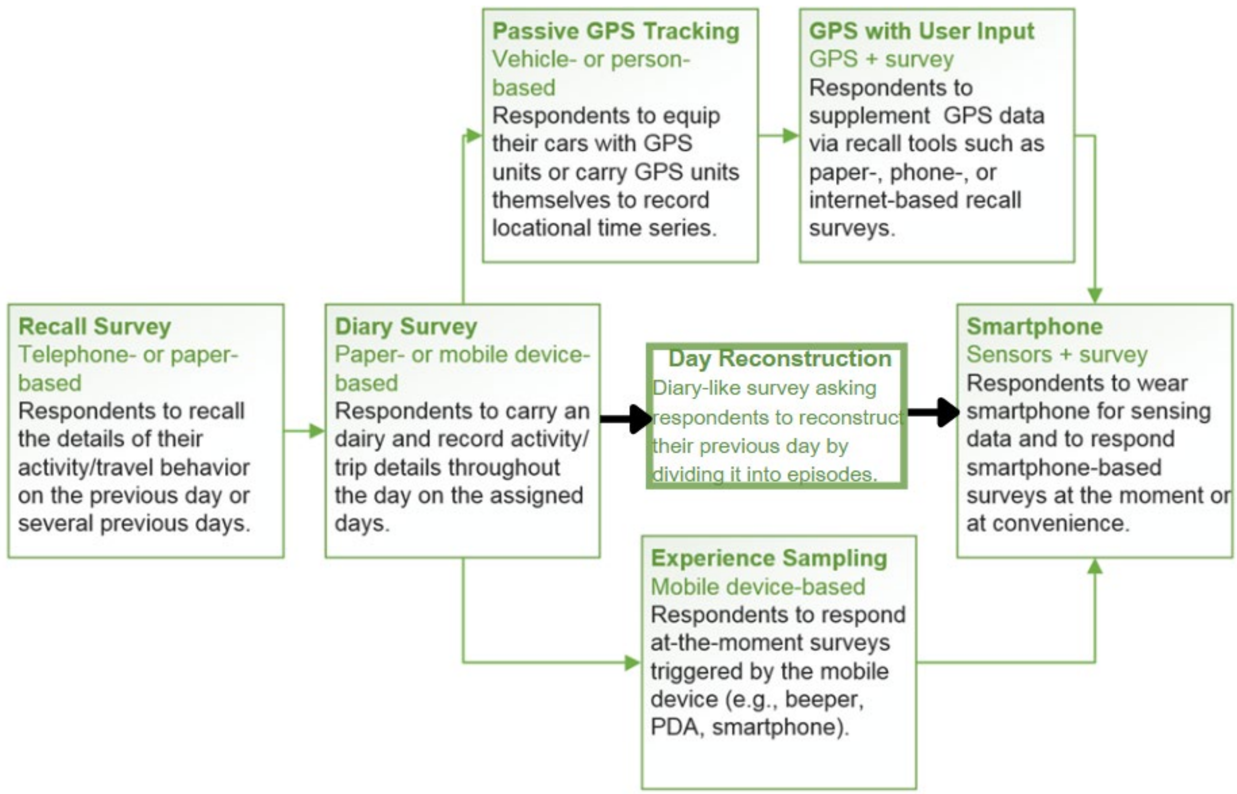


Figure 1. Methodological evolution in activity-travel data collection

Recall Survey

The recall survey approach, which is often phone- or paper-based, asks respondents to recall characteristics of their activity and travel behavior (such frequency, duration, and distance) on one or more days. This data is prone to recall bias and low-resolution because respondents often do not memorize precise details, such as activity start and end time, trip arrival and departure times, and travel distances and routes (Bohte & Maat, 2009).

Diary Survey

In the late 1990s, there was a shift from recall-based surveys to activity and travel diaries that require respondents to carry their diary on assigned days and record activity and trip details throughout the day. While diaries do reduce recall bias when used correctly, many participants find that taking detailed notes on each activity and trip throughout the day is burdensome. Consequently, participants often postpone filling in their diaries, which leads to significant recall bias in diary-based data collection efforts (Bohte & Maat, 2009; Schlich & Axhausen, 2003; Schönfelder et al., 2002).

Day Reconstruction Method (DRM)

DRM was first introduced by psychologist Daniel Kahneman and his colleagues in a study published in 2004. It is a detailed diary-like survey technique which asks respondents to reconstruct their previous day by dividing it into discrete episodes or segments. For each segment, participants provide details such as the activity they were engaged in, the time it occurred, the location, the people they were with, and their feelings or emotional state during that time. This innovative method was developed to provide a more detailed and accurate account of individuals' daily activities and emotional experiences.

Passive GPS Tracking

To reduce the burden placed on respondents in traditional recall and diary surveys, Global Positioning Systems (GPS) have gained popularity in recent activity and travel data collection efforts. GPS units have the advantage of providing accurate, second-by-second data on location and velocity, which enables automatic collection of precise trip origin and destination data, trip route data, and trip start and end time data. Initially, GPS tracking of travel behavior was vehicle-based: cars were equipped with GPS units to record information when the vehicle was running. Such technology has shortcomings because it excludes non-motorized travel modes and does not provide reliable information on the real origins or destinations, as origins and destinations tracked by vehicle-based GPS are often garages or parking lots. (Du & Aultman-Hall, 2007).

More recently, improved technology has led to the use of individual-based GPS units to collect travel behavior data across multiple modes. However, extracting meaningful travel behavior information from raw GPS data require intense offline data processing efforts that must be carried out separately from GPS data collection (Schuessler & Axhausen, 2009). The processing efforts often include GPS data filtering, trip detection, and map matching. For example, speed and location change thresholds are often used to distinguish trip segments from stationary segments and distinguish motorized trip segment from non-motorized trip segments. External land-use and points-of-interest data are often used in conjunction with GPS data to predict activity location types and trip purposes (McGowen & McNally, 2007; Srinivasan et al., 2006).

GPS Tracking with User Input

No matter how sophisticated the classification rules or prediction models are in interpreting raw data collected from passive GPS tracking, results from classification and prediction inevitably contain errors and inaccuracies. Moreover, activity and travel behavior have many other important dimensions—such as experience and companionship—that may be impossible to infer from pure GPS data. To address this issue, researchers have begun supplementing GPS data with user input. This method primarily involves combining GPS data with recall or diary tools (Gong et al., 2012; Doherty et al., 2006; Li & Shalaby, 2008). The GPS data, combined with user input data, provide richer and more accurate information on activities and trips throughout the day than data generated from the use of passive GPS tracking alone or traditional survey and diary methods alone.

Experience Sampling

Activity and experience sampling is another technique that has been developed to minimize recall bias and improve accuracy in activity and travel behavior data. This method focuses on getting real-time activity and travel information from respondents using a mobile signaling device, such as pager or a cell phone to prompt participants to respond to answer questions at random times throughout the day. The questions often include queries on what the respondent is currently doing, their physical and social context, and how many people are with them. Survey triggering of this kind can yield accurate information about activity and travel, but comes with two major disadvantages (Hektner et al., 2007). First, because activity and travel information are collected at random time points of the day, it does not provide continuous information on activity and travel behavior throughout the day. Second, it is often inconvenient and intrusive for study subjects as they are prompted to complete surveys several times a day, regardless of convenience.

Smartphone

Smartphone technology is more advantageous than GPS with user-input because smartphones come with built-in GPS receivers and a convenient user interface for gathering input. In addition to GPS, smartphones also have other built-in sensors such as accelerometers, magnetometers, and gyroscopes. As a result, it is easy for smartphones to seamlessly combine multiple data collection modules with a single device (Nitsche et al., 2014; Wan & Lin, 2013). The activity and experience sampling technology can also be easily implemented in smartphones with their ability to signal respondents and gather real-time input from the respondents. The smartphone-based methods have enabled the collection of both sensor data and user-input data on daily activities and trips (either in real-time or at the user's convenience) in a single device.

The DDR Difference

The DDR-based Daynamica app allows users to conduct their daily activities as the app automatically collects data. Occasionally, the user may open the app to edit or confirm the data collected; for example, they could edit the activity type classification or the start- and end- time of an event. In this way, the app collects both continuous and momentary information about users' daily activities and experiences. Figure 2X shows the way in which Daynamica improves upon the previously discussed method's four performance dimensions: respondent burden minimization, data comprehensiveness, data accuracy, and ease of distribution and management.

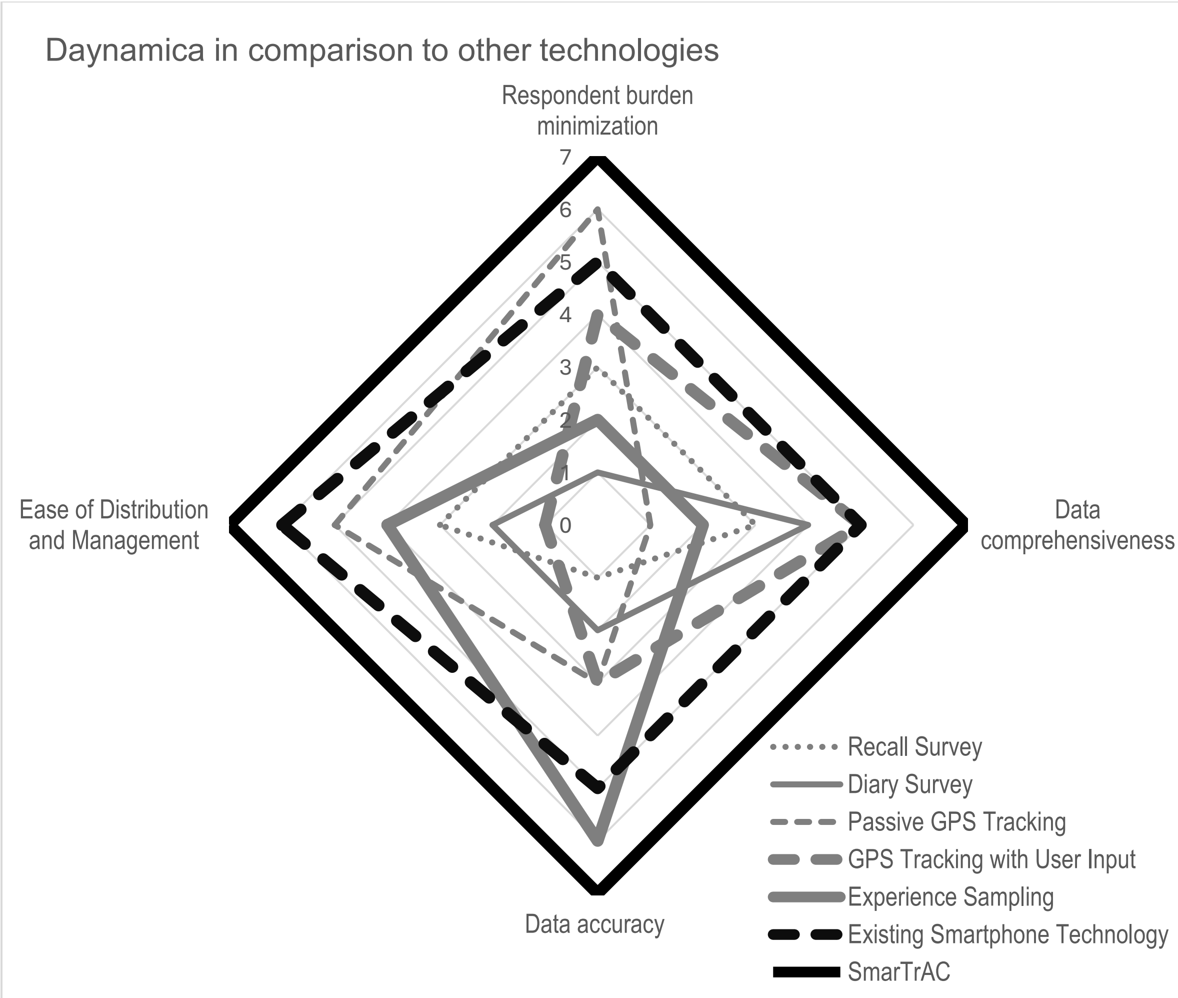


Figure 2. Performance Comparison: DDR-based Daynamica vs. other data collection methods

As shown in Figure X, Daynamica is advantageous on each of the dimensions below:

- **Respondent burden minimization:** Daynamica does not require respondents to carry or use additional devices or instruments if the respondents already own a smartphone. Daynamica is also more advantageous than existing smartphone technology that uses only smartphone-based sensing and surveying functions, because Daynamica processes sensor data using machine learning techniques to extract meaningful activity data to minimize the amount of input needed from the user.
- **Data comprehensiveness:** Daynamica represents the best of many worlds. It is better than diary-like recall surveys (including DRM) alone or passive GPS tracking alone because it uses built-in sensors to capture time data, as well as additional user input data. It outperforms experience sampling (even when embedded within smartphone technology) because experience sampling requests user input at random times while Daynamica allows user input at any moment. Daynamica surpasses existing smartphone-based methods and GPS-with-user-input methods by using information extracted from sensor data to form an

information basis for the user to provide additional inputs; existing smartphone-based methods and GPS-with-user-input methods obtain sensor data and user-input data separately, even if the data are obtained from a single device.

- **Data accuracy:** Daynamica provides advantages over other technologies because it allows sensor data to interact with user input data such that the two data sources can calibrate with each other. In this way, Daynamica minimizes recall bias or reporting errors in user-input data because the user can access information derived from sensor data when providing user input.
- **Ease of distribution, management, and post-processing:** Daynamica does not involve providing additional devices or instruments to respondents if they already own a smartphone, making easier to distribute and manage than other technologies; users only need to download the Daynamica app and install it on their phone. Periodic updates (for example, adding new features or tweaking machine-learning algorithms) can be provided to users quickly and easily. In addition, Daynamica collects activity and travel data in a way that reduces the need for post-processing by generating both raw time series data and summarized episode-level data on activity and travel behavior. Both types of data can be transmitted to any secured network storage space using cell phone or wireless networks. Transmitted data can be checked for quality and consistency, and any necessary modifications or adjustments to the data collection process can be made quickly.

Chapter Summary & Conclusions

In summary, the innovative Daynamica smartphone application is a powerful, two-pronged tool that collects and processes highly detailed activity data with minimal user burden. It combines mobile sensing with advanced statistical and machine learning techniques to automatically detect, identify, and summarize attributes of daily activities. Users can then view, correct, and provide additional contextual and experiential information on the activities at their convenience anytime, at home or on the go. Data from these two sources—the sensors and the users—interact to inform, calibrate, and augment each other:

- Sensor data are analyzed and processed locally on the smartphone in real time to extract meaningful activity and travel information. The extracted information serves as a basis to prompt the user for more detailed and more accurate information.
- The user-entered data, in turn, optimizes how the sensor data are analyzed and processed. This increases the accuracy of the information extracted from sensor data over time—the algorithm "learns" about a user's routine travel locations and behaviors—so that the user needs to make fewer updates or corrections.

The open-source app is a compelling alternative to the traditional diary-based method typically used to collect individual travel and activity information. It delivers richer, more accurate data—more efficiently and at lower cost.

It is important to note that any research tool (no matter how powerful) must be used with care, because the study of human behavior and experience presents challenges and ethical considerations. Researchers must navigate issues related to privacy, consent, cultural sensitivity, and the potential for bias in their methodologies and interpretations. Ethical guidelines and rigorous peer review processes are essential to ensure that research is conducted responsibly and contributes positively to our understanding of human behavior and societal development.

The study of human behavior and life is a dynamic and ever-evolving field. Continued innovation in this field requires partnership and team science, which has been reflected in my approach to the development of Daynamica: while my work is rooted in urban planning and social sciences, I believe good scholarship means being disciplinarily unmoored and forming interdisciplinary and cross-sector teams. With this mindset and the power of Daynamica's DDR capabilities, we can gain profound insights into the essence of what it means to be human and how we can build better societies for future generations.

References

Ambrose, Graham, Kirti Das, Yingling Fan, and Anu Ramaswami. "Is gardening associated with greater happiness of urban residents? A multi-activity, dynamic assessment in the Twin-Cities region, USA." *Landscape and Urban Planning* 198 (2020): 103776.

Ambrose, Graham, Kirti Das, Yingling Fan, and Anu Ramaswami. "Comparing happiness associated with household and community gardening: Implications for Food Action Planning." *Landscape and Urban Planning* 230 (2023): 104593.

Becker, Andrew B. *Clustering Methods for Correlated Data*. *Ph.D. Dissertation*. University of Minnesota (2022).

Bohte, Wendy, and Kees Maat. "Deriving and validating trip purposes and travel modes for multi-day GPS-based travel surveys: A large-scale application in the Netherlands." *Transportation Research Part C: Emerging Technologies* 17, no. 3 (2009): 285-297.

Brown, Roland. "A Statistical Framework for Harnessing Human Activity Data to Understand Behavior, Health, and Well-Being." *Ph.D. Dissertation,* University of Minnesota (2020).

Das, Kirti Vardhan. "Assessing the influence of the neighborhood environment on evaluative and emotional subjective well-being." *Ph.D. Dissertation., University of Minnesota* (2020).

Doherty, Sean T., Dominik Papinski, and Martin Lee-Gosselin. "An internet-based prompted recall diary with automated GPS activity-trip detection: System design." *Washington, DC* (2006):22-26.

Du, Jianhe, and Lisa Aultman-Hall. "Increasing the accuracy of trip rate information from passive multi-day GPS travel datasets: Automatic trip end identification issues." *Transportation Research Part A: Policy and Practice* 41, no. 2 (2007): 220-232.

Erinne, Jacquelyn O., "Travel behavior and subjective well-being: Effects of travel, activity, and personal factors". *Ph.D. Dissertation*. Mississippi State University (2022).

Erinne, Jacquelyn, Alireza Ermagun, and Yingling Fan. "Just because I'ma woman: Gender happiness gap in human mobility." *Travel behaviour and society* 29 (2022): 224-235.

Ermagun, Alireza, Jacquelyn Erinne, and Yingling Fan. "Travel duration tolerance: Examining the sensitivity of emotional well-being to trip duration." *Transportation research part D: transport and environment* 102 (2022): 103137.

Ermagun, Alireza, Yingling Fan, Julian Wolfson, Gediminas Adomavicius, and Kirti Das. “Real-time trip purpose prediction using online location-based search and discovery services.” *Transportation Research Part C: Emerging Technologies* 77 (2017): 96-112

Fan, Yingling, Andy Becker, Galen Ryan, Julian Wolfson, Andrew Guthrie, and Chen-Fu Liao. “Smartphone-Based Interventions for Sustainable Travel Behavior: The University of Minnesota Parking Contract Holder Study.” *University of Minnesota Center for Transportation Studies Report 20*-13 (2020).

Fan, Yingling, Julian Wolfson, Gediminas Adomavicius, Kirti Vardhan Das, Yash Khandelwal, and Jie Kang. “SmarTrac: A smartphone solution for context-aware travel and activity capturing.” *Center for Transportation Studies at the University of Minnesota* (2015).

Fan, Yingling, Qian Chen, Chen-Fu Liao, and Frank Douma. “Smartphone-based travel experience sampling and behavior intervention among young adults.” Report no. CTS12-11. (2012).

Fan, Yingling, Wolfson, J., and Adomavicius. G. Travel and activity capturing. US Patent 9,763,055, filed Aug. 26. 2015, and issued (Dec. 21. 2021).

Fan, Yingling, Roland Brown, Kirti Das, and Julian Wolfson. “Understanding trip happiness using smartphone-based data: the effects of trip- and person-level characteristics.” *Transport Findings.* (2019).

Gong, Hongmian, Cynthia Chen, Evan Bialostozky, and Catherine T. Lawson. “A GPS/GIS method for travel mode detection in New York City.” *Computers, Environment and Urban Systems* 36 no. 2 (2012): 131-139.

Hektner, Joel M., Jennifer Anne Schmidt, and Mihaley Csikszentmihalyi. “Experience sampling method: Measuring the quality of everyday life” *Sage* (2007).

Lal, Raj M., Kirti Das, Yingling Fan, Karlone K. Barkjohn, Nisha Botchwey, Anu Ramaswami, and Armistead G. Russell. “Connecting air quality with emotional well-being and neighborhood infrastructure in a US city.” *Environmental Height Insights* 14 (2020): 1178630220915488.

Lal, Raj M., Kirti Das, Yingling Fan, Karlone K. Barkjohn, Nisha Botchwey, Anu Ramaswami, and Armistead G. Russell. “Connecting air quality with emotional well-being and neighborhood infrastructure in a US city.” *Environmental Height Insights* 14 (2020): 1178630220915488.

Li, Zhigang, and Amer S. Shalaby. “Web-based GIS system for prompted recall of GPS-assisted personal travel surveys: System development and experimental study.” In *Masters Abstracts International* 46, no. 6 (2008).

Martin, Bryan D., Vittorio Addona, Julian Wolfson, Gediminas Adomavicius, and Yingling Fan. “Methods for real-time prediction of the mode of travel using smartphone-based GPS and accelerometer data.” *Sensors* 17, no. 9 (2017): 2058.

McGowen, Patrick, and Micheal McNalley. “Evaluating the potential to predict activity types from GPS and GIS data.” In *Transportation Research Board 86th Annual Meeting* (2007).

Nitsche, Philippe, Peter Widhalm, Simon Breuss, Norbert Brändle, and Peter Maurer. “Supporting large-scale travel surveys with smartphones—A practical approach.” *Transportation Research Part C: Emerging Technologies* 43 (2014): 212-221.

Schlich, Robert, and Kay W. Axhausen. "Habitual travel behaviour: evidence from a six-week travel diary." *Transportation* 30 (2003): 13-36.

Schönfelder, Stefan, Kay W. Axhausen, Nicolas Antille, and Michel Bierlaire. "Exploring the potentials of automatically collected GPS data for travel behaviour analysis: A Swedish data source." *Arbeitsberichte Verkehrs-und Raumplanung* 124 (2002). Available at https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/146755/eth-25715-01.pdf

Schuessler, Nadine, and Kay W. Axhausen. “Processing raw data from global positioning systems without additional information.” *Transportation Research Record* 2105, no. 1 (2009): 28-36.

Srinivasan, Sivaramakrishnan, Prabudda Ghosh, Aruna Sivakumar, Aarti Kapur, Chandra R. Bhat, and Stacey Bricka. “Conversion of Volunteer-Collected GPS Diary Data into Travel Time Performance Measures: Final Report.” *Transportation Research Board* (2006).

Tao, Tao, Xinyi Wu, Jason Cao, Yingling Fan, Kirti Das, and Anu Ramaswami. "Exploring the nonlinear relationship between the built environment and active travel in the twin cities." *Journal of Planning Education and Research* 43, no. 3 (2023): 637-652.

Wan, Neng, and Ge Lin. “Life-space characterization from cellular telephone collected GPS data.” *Computers, Environment and Urban Systems* 39 (2013): 63-70.

Wang, Jeuyu. “Beyond Accessibility and Behavioral Outcomes; Re-conceptualizing Equity in Transportation through the Capabilities approach.” *PhD diss., University of Minnesota* (2020).

Wang, Jueyu, Greg Lindsey, and Yingling Fan. "Exploring the interactions between modal options, destination access, and travel mood." *Transportation research part F: traffic psychology and behaviour* 82 (2021): 450-461.

Wu, Xinyi, Tao Tao, Jason Cao, Yingling Fan, and Anu Ramaswami. "Examining threshold effects of built environment elements on travel-related carbon-dioxide emissions." *Transportation Research Part D: Transport and Environment* 75 (2019): 1-12.