Health and Medical Behavior Informatics

Longbing Cao

Advanced Analytics Institute, University of Technology Sydney

Abstract

Behavior matters, and behavior informatics is the approach to discover and apply behavior intelligence and value for behavior-related problem-solving and interventions. Health behavior research and behavioral medicine take a behavior-centric approach and have been explored for decades in the health and medical communities. However, understanding, analyzing and managing health and medical behavior from an informatics perspective has not been systematically explored, with very limited progress made. In this paper, we discuss the research areas, concepts, research topics, and applications of health behavior informatics and medical behavior informatics. A conceptual framework of health and medical behavior informatics is introduced, together with a brief overview of behavior informatics. We focus on the discussion opportunities of health and medical behavior informatics, and their connections to health behavior research, behavioral medicine, and data science and artificial intelligence.

Keywords: Behavior informatics, behavior computing, behavior modeling, behavior analytics, health behavior, health behavior research, medical behavior, behavioral medicine, health behavior informatics, medical behavior informatics

1. Introduction

The role of behaviors and behavior insight and intelligence [1] has been increasingly recognized in understanding the activities and their impact taking place in the physical world especially in recent 10 years [2, 3]. Behaviors matter [4] as they bridge the gaps between the simplified data world and the rich

physical world, behaviors are the language and media for understanding the nature, intrinsic characteristics, working mechanisms, and dynamics (including what has happened, is happening or will happen) of a physical world and its phenomena, outcomes and their evolution [5].

Accordingly, several important concepts, such as *behavior informatics* [6], *behavior computing* [7], *behavior analytics* [2] and *behavior modeling* have been proposed and discussed in the recent literature. Major attention has been transferred from 'soft' behavior analysis to 'hard' behavior analytics [2], which involves subjects (actors) and what they have 'behaved', i.e., their activities [8, 9], actions [10], and interactions [11] in a certain context.

On the other hand, the applications of behavior informatics (exchangeable in this paper with the above concepts such as behavior computing) have been increasingly expanded for real-life decision-making. Typical applications cover such areas as capital market behavior analysis (behavioral finance) [12], the interactions between government units and citizens [13], online behavior analysis [14], and visual behavior analysis [15], to name a few.

In the health and medical domains, the importance of exploring health and medical problems, interventions and outcomes has been well recognized over 40 years ago [16]. Two major research directions have been explored: health behavior research [17] and behavioral medicine [16]. By reviewing the difference and connections of the motives, perspectives and approaches between behavior informatics and these two research areas, we see the value and necessity of upgrading health behavior research and behavioral medicine to health behavior informatics and medical behavior informatics. In this way,

- health and medical behaviors are more completely, deeply, systematically, and scalably understood, analyzed, evaluated and managed by informatics approaches;

- we are able to discover latent yet significant behavior insight and behavior intelligence for smarter and personalzied prediction, prevention, intervention and rehabilitation of health and medical problems and more cost-

effective resource planing, risk management, and health/medical service quality evaluation etc.; and

- health and medical problem-solving and decision-making can be better and more complementarily informed by sequential, dynamic and relevant behaviors (behavioral data), sound and actionable evidence discovered in the behavioral data.

Accordingly, in this paper, we would like to paint a high-level picture of the behavior informatics of health and medical behaviors, i.e., introduce the concepts of *health behavior informatics* and *medical behavior informatics*, in the context of a brief overview of behavior informatics from a general perspective and of the related work on health behavior and behavioral medicine. Accordingly, this paper consists of the following parts. Section 2 presents a brief overview of the concepts of behavior, behavior informatics and their applications. In Section 3, we explore health and medical behaviors and their modeling, representations, analysis, intervention, and management in the health and medical businesses. Section 4 introduces the concepts and opportunities of health and medical behavior informatics. Section 5 discusses the connections to health behavior research, behavioral medicine, and health informatics. Lastly, in Section 6, we discuss several prospects of health and medical behavior informatics by linking them to the current advancement of data science and artificial intelligence.

2. Behavior and behavior informatics

In this section, we briefly review some of major concepts: behavior, behavior informatics, and the applications of behavior informatics. These lay a foundation for further discussion on health behavior, medical behavior, health behavior informatics, and medical behavior informatics.

2.1. Behavior

We categorize the relevant definitions of behavior into soft behavior and hard behavior. *Soft behavior* refers to a virtual or nominal notation applicable to anything that may be, but not necessarily, related to an action [10], activity [9], interaction [11], or event [18], as well as any observations and appearances. For example, a student's learning behavior generally refers to broad learning aspects related to a student.

In contrast, *hard behavior* is centered on an action, activity, interaction, or event, typically on a sequence of actions, activities, interactions, or events in a context. For example, a hard definition of learning behaviors refers to the activities and processes related to a student's learning.

In this paper, we coin the concept of behavior in terms of hard behavior, while also respect the diverse scopes used in health behaviors and behavioral medicine. In this sense, a *behavior* consists of an action; its undertaking time, place, state, constraint and context; its driving goal, intent, belief and plan; its related process (action sequence); its behaving subject and applied object; and the effect, impact, cost, utility etc. of the behavior [6]. These aspects are called *behavior elements*, which form an *abstract behavior* and a *behavior model* [6]. Here, behavior subjects and objects can be any entities, including humans or non-human entities (e.g., a patient, a doctor, a hospital, or a medical device).

Building on an atomic behavior unit, i.e., the above discussed behavior, a *behavior sequence* or a *behavior network* can be then constructed to connect all behaviors taken place in a period of time, undertaken by target subjects and on relevant objects, forming *individual behaviors* or *group behaviors*. In a behavior sequence or network, behaviors and their elements are connected in terms of various behavior relations. *Behavior relations* (or behavior couplings) [19, 9] refer to the relationships between behavior elements, between behaviors, between behavior subjects and objects, and/or between behavior impact. Behavior impact [20, 21, 22] refers to the effect of behaviors (individual, group or sequential behaviors), which may be measured in terms of effect and impact on business, behavior utility [23, 24, 25], and other aspects, e.g., cost and change

of conditions.

Accordingly, an *abstract behavior model* consists of the demographics and circumstances of behaving subjects and behaved objects; a sequence or network of behaviors; the contextual factors, constraints, social relationships and norms; and the impact, cost, risk and trust of a behavior or a behavior network.

More discussion on the concept of behavior and the abstract behavior model can be found in [6, 26, 8, 7].

For example, in capital market, a trading behavior may be placing a buy order in a market orderbook, which is affiliated with the buy time, buy price, buy volume, the security bought, and the counterpart trader (from whom the order was purchased), etc. The buy order is further associated with other buyers, sellers and holders as well as their behaviors in the market; affected by the market price movement, in-market and out-market factors; and may also affect other buys, sells, withdrawals, and holdings. A buy order under a particular context was made based on the buyer's investment intent and goal; the belief on the market dynamics, internal and external factors, and the possible return on investment; and the possible cost, risk and impact of placing the buy order.

A decent understanding of behavior requires the construction of behavioral data. *Behavioral data* refers to the data that is centered on behavior, which is typically described by a behavior feature space. A *behavior feature space* consists of various behavior elements as discussed in the above behavior model to describe an individual, group, or sequence of behavior.

The typical entity-relationship-based transactional data is not behavior-centric, rather entity-oriented [2]. In existing database, data warehouse and Hadoop-based storage management, behaviors taken place in physical worlds are decomposed and transformed to entity-relationship-based or key-value-based representations. It is not possible to have a sound behavior understanding directly on top of such data transactions. It is essential to convert these transactional data to behavioral data, and construct a behavior feature space through behavior modeling and behavior representation [6, 27].

2.2. Behavior informatics

The concept *behavior informatics* was first introduced in [26, 6]. It was built on the comprehensive understanding and relevant work on behavior analysis [4] in behavioral science, activity analysis [8] of activity/action sequences, action recognition [10] in computer vision, and user modeling, and broad aspects of behavior-related modeling, analysis, mining, learning, and processing [28], etc.

Behavior informatics refers to the methodology and relevant methods and tools for the modeling, representation, processing, analysis, learning, management, and application of behaviors. A conceptual map of behavior informatics is presented in Figure 1, which consists of main research directions of behavior representation and reasoning, behavior analysis and learning, behavior measurement and evaluation, behavior presentation (including user-machine interaction) and management, and behavior-oriented decision, intervention and applications. Below, we briefly introduce three aspects: behavior representation and reasoning, behavior analysis, learning and evaluation, and behavior management and applications.

2.2.1. Behavior representation reasoning

Taking a top-down approach to model behaviors, the research on behavior representation and reasoning involves behavior representation (behavior modeling), behavior reasoning, behavior aggregation, and behavior model checking, etc. [9, 27].

- Behavior representation: developing theories and methods for modeling and representing behaviors, behavior sequences, and behavior networks etc. by considering behavior elements, behavior relations, behavior structures, behavior dynamics, behavior context, and relevant impact (including cost) etc. in visual and/or formal languages and methods.

- Behavior reasoning: developing theories and methods for reasoning about behaviors, behavior states, behavior relations, behavior structures, and

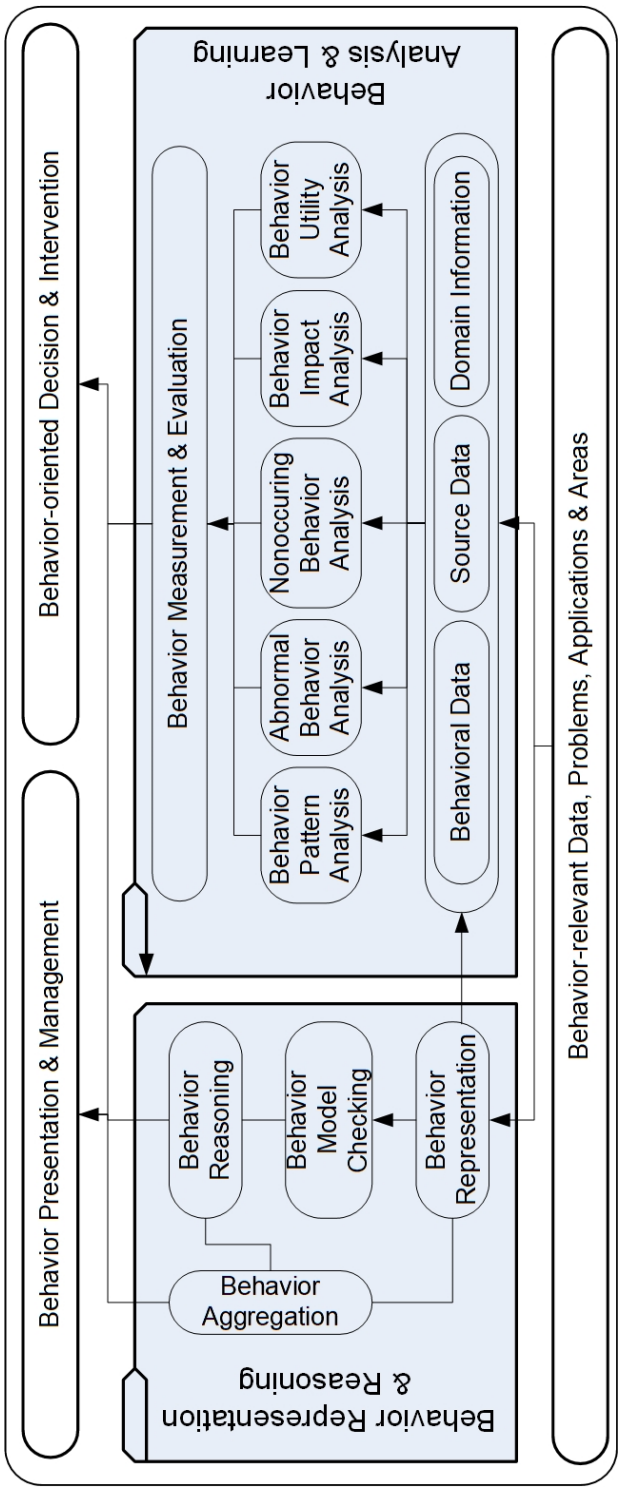

Figure 1: A research map of behavior informatics.

behavior dynamics, typically by defining reasoning and inference rules in a logical or probabilistic manner.

- Behavior aggregation: developing theories and methods for aggregating behaviors, behavior states, behavior relations, behavior structures, and behavior networks, typically by defining and deriving aggregation rules in a logical, mathematical or probabilistic manner.

- Behavior model checking: developing model-checking theories and methods for ensuring the properties, functions, validity, robustness, and effectiveness of behavior models and behavior representers, and resolving issues (such as deadlocks) caused by the modeling, reasoning and/or aggregation.

An important output of behavior representation and reasoning is the capabilities of constructing and formalizing behavior models and behavioral data, extracting behavior relations and behavior structures, condensing and refining behavior models, states and networks for an individual or a group of subjects. All of these are fundamental for forming a *behavior world* to project what has happened, is happening or will happen in a physical world to a behavior world, and for conducting decent, sound, and in-depth behavior understanding, analytics and management.

2.2.2. Behavior analysis and learning

In contrast, behavior analysis and learning takes a bottom-up approach to understanding behaviors. It can be decomposed into many specific research areas and topics by targeting specific problems, scenarios, objectives and/or requirements, for example, action recognition, behavior pattern analysis, abnormal behavior analysis, nonoccurring behavior analysis, behavior impact analysis, behavior utility analysis, visual behavior analysis, and behavior-oriented measurement and evaluation.

- Action recognition: developing theories and methods to recognize and annotate actions, behaviors, behavior sequences, or behavior scenarios typically in images or videos (e.g., [10]).

- Abnormal behavior analysis: developing theories and methods to detect, analyze and quantify abnormal behaviors, abnormal behavior sequences, abnormal behavior dynamics, abnormal evolving behaviors, or abnormal behavior impact (e.g., [29]).

- Behavior pattern analysis: developing theories and methods to represent, analyze, and discover patternable behaviors, impact-oriented behaviors and evolving behaviors, broadly called *behavior patterns*, of individuals or a group of subjects or objects, typically in occurring behavioral data (also called positive behavior patterns) (e.g., [20]).

- Nonoccurring behavior analysis: developing theories and methods to represent, analyze, and discover nonoccurring behaviors, nonoccurring behavior patterns (called negative behavior patterns), and the dynamics and impact of nonocurring behaviors [30] (e.g., [31]).

- Behavior impact analysis: developing theories and methods to represent, quantify, analyze, intervene or manage the qualitative and/or quantitative effect and impact (e.g., business impact, environmental impact) of undertaking a behavior or behavior sequence on another behavior or behavior sequence, on objects, or on the behavior-related context or environment (e.g., [20]).

- Behavior utility analysis: developing theories and methods to represent, quantify, analyze, intervene or manage the utility of undertaking a behavior or behavior sequence, as a perspective of undertaking behavior impact, typically for discovering high utility-based behaviors (e.g., [24, 25]).

- Visual behavior analysis: developing theories and methods to represent, detect, recognize, annotate, analyze, mimic, or simulate actions, behaviors, behavior sequences, and behavior scenarios in visual data (images or videos) (e.g., [15]).

- Behavior-oriented measurement and evaluation: developing theories and

methods to measure and evaluate the technical (e.g., statistical) or business (e.g., utility or impact) significance of a behavior analysis and learning task, theory or method, and result.

The resultant theories and methods for behavior analysis and learning form the capabilities and capacity of quantifying, processing, analyzing, learning, and managing behaviors, behavior networking, and their effect and impact. These enable us to build an intrinsic and quantitative understanding of the behavior world and thus its underlying physical world.

2.2.3. Behavior management and applications

Lastly, behavior management and applications synergizes behavior representation and reasoning and behavior analysis and learning, and develops theories, methods, and applications to take advantage of or manage and control behaviors. These may result in diverse research areas and application scenarios, for example, behavior management system, behavior simulation, imitation learning, behavior replay, and domain-specific behavior applications.

- Behavior management system: developing solutions, architectures, infrastructures, modules, and interfaces to enable the acquisition, management, intervention, control, and export of behaviors, behavior elements, behavior sequences or networks, and behavior effects in the context of domain-specific behavior-related problems and applications.

- Behavior simulation: developing theories, methods, tools and systems to support the simulation, adjustment and refinement, and management and control of behaviors and their effects in a certain context or environment.

- Imitation learning: developing theories, methods, tools and systems to mimic, copy, follow, reinforce and optimize learning from observations and demonstrations, which can be behavior-oriented, e.g., reconstructing the behaviors of subjects within a certain environemnt in a video (e.g., [32]).

- Behavior replay: developing theories, methods, tools and systems to enable the replay of what has happened and is happening in the physical world, the exploration of the scenarios, the analysis of driving factors, the testing of stimulation and response, and the discovery of insights for managing behaviors and their effects.

- Behavior presentation: developing solutions, architectures, infrastructures, modules, and interfaces to present behaviors, behavior elements, dynamics, relations, driving factors, and effects, typically in qualitative (e.g., rules, visualization, graphs) and/or quantitative (e.g., statistical, probabilistic, or logic forms) for human readability and domain-specific behavior-driven display and interaction with end users or stakeholders.

- Domain-specific behavior applications: built for a specific domain or domain-specific problem, various applications of behavior representation, modeling, analysis, learning, and management can be created to address real-world problems and achieve practical goals that cannot be possible directly in the physical world or the data world.

The above three research areas, i.e., behavior representation and reasoning, behavior analysis and learning, and behavior management and applications, are interconnected and coupled with each other, forming a necessary and sufficient system for understanding and managing behaviors.

- Behavior representation and reasoning extracts behaviors and makes behaviors visible and machine readable, forming a fundamental system for visibly and deeply representing what has happened, is happening or will happen in the underlying physical world, which cannot be achieved by exploring the data world simply projected from the physical world.

- Behavior analysis and learning further makes behaviors computable, analytical and interesting, playing the role of disclosing how the physical world behaved, is behaving or will behave, and possibly its driving forces, causes and effects.

- Behavior management and applications make behaviors valuable and manageable, creating capabilities of taking advantage of or managing and controlling what has happened, is happening or will happen in the physical world.

2.3. Applications of behavior informatics

The applications of behavior informatics are highly valuable and widely applicable to any behavior-related problems, domains, and objectives. The second major part of this paper is to illustrate possible applications of behavior informatics in the health and medical domains. In addition, we list a few real-world projects we have conducted in recent years that invented and applied behavior informatics for an innovative and deep understanding, a smarter management and decision-making, and a better practice and outcome of the underlying problems in several domains, in comparison with data-driven (we mean based on the existing data systems that are non-behavior-oriented) approaches.

- Smart market surveillance in capital markets: the theories and methods of behavior informatics were developed to detect pool manipulations (a group of investors aim to manipulate the price movement of a security or a series of securities) [29] and financial crisis analysis [33] in capital markets by the method of *coupled behavior analysis*, i.e., modeling group behaviors that are coupled with each other w.r.t. coupled hidden Markov models [19] or probabilistic models [34].

- Smart trading in capital markets: better and more actionable trading strategies were created that analyze trader behaviors for generating more promising or less-risky trading positions and signals in capital markets [35, 36].

- Active client engagement in the taxation service: taxpaying behaviors and the interactions between taxation officers and taxpayers were analyzed for detecting risky client behaviors that may indicate the overclaim of tax or underclaim of income, and for informing an active engagement

with taxpayers for earlier, faster and/or more recovery of overclaimed tax, earlier and easier repayment of habitual repayment delay, and early-warning of possible future overclaims [13].

- Detection, recovery, and prevention of overpayments in social welfare services: by constructing the declared activity sequences of social welfare clients and their interactions with the government, overpayments were detected and predicted, with repayments arranged for earlier, faster or more recovery and prevention [20, 37].

- Risk management of undeclared client activities in government services: by identifying those undeclared activities that should be declared but were missing (e.g., additional cash received or frequent change of business addresses), their associated risk (e.g., overpayments caused by missing the reduction of allowance eligibility in social welfare) were analyzed [38].

3. Health and medical behavior

Many of health and medical problems are behavioral or behavior-related, and such behaviors matter in many important health and medical objectives [4]. Here, we summarize different types, sources, and perspectives of health behaviors and medical behaviors.

3.1. Health behavior

There are different definitions for health behaviors given in the literature. In this work, *health-related behaviors*, or simply *health behaviors*, refer to broad types of actions that maintain, are related to, determine or influence the health and well-being and prevent the illness of an individual, a group, or an organization. In the professional communities of health and psychology, the four focus behaviors mostly concerned are smoking, drinking, diet, and physical activities [39]. Other health behaviors typically concerned include lifestyles, sexual activities, screening tests, medication-taking, and vaccinations.

Progressively, health behaviors have attracted increasingly widespread and diversified attention in not only the healthcare, public health, epidemiological, anthropoligical, psychological, and medical care communities but also enviornmental, sociological, cultural, educational, and information and technological service communities for about five decades [40, 41, 42, 43]. These perspectives of health behavior viewpoint and exploration go beyond the above professional views of health behaviors.

Accordingly, there are different action types, behavioral factors, categorization criteria, perspectives, methods and models to define, specify and classify health behaviors. In saying this, we refer both soft and hard health behaviors. Here, we summarize various health behaviors in terms of personal vs. public, individual vs. group, specific vs. general, physical vs. mental, observable/overt vs. inner/covert, lifestyle-related vs. medical, healthy vs. unhealthy, and preventive vs. healthcare determinants, activities, perspectives, states, factors and/or objectives.

- Personal vs. public: the activities, aspects and factors and personal attributes and habits that are related to an individual's health and quality of life, which may involve aspects of physical, dietary, lifestyle-related, mental, habitual, etc. activities and factors (e.g., daily physical and dietary activities); and the activities and factors that relate to the public health and health practice, which may involve very broad aspects, e.g., of social, economic and environmental activities and factors, and public policy and education;

- Individual vs. group: the health-related activities and factors of individuals share some common behaviors of a group (or a population) that the individuals belong to while also incorporate personalized activities, contexts, and socioeconomic and environmental factors; and the activities of a group or an organization;

- Specific vs. general: the specific activities and factors related to an individual/group's health and life quality (e.g., a person's diet-specific daily

activities and habits); and the general and broad aspects and activities related to a community/society or lifestyle-related broad aspects (e.g., public health services and policies for preventive health improvement);

- Physical vs. mental: the physical activities undertaken by an individual or a group; and the activities and factors that are related to mental and emotional states, traits, personality, habits, a person's values, beliefs, motives, and psychological and cognitive elements;

- Observable/overt vs. inner/covert: physical health behaviors are often observable and overt; while the psychological and personality-related traits, states and activities are typically inner and covert;

- Lifestyle-related vs. medical: the activities that are related to individual/group's dietary behaviors, substance usage and living styles and conditions (e.g., consumption habit of alcohol and tobacco, eating patterns and drinking preferences); and the activities or medical behaviors that are related or contribute to morbidity, disability, disease, mortality or death (e.g., overdose of drugs);

- Healthy vs. unhealthy: the healthful activities, habits, factors and lifestyles that contribute to health restoration, maintenance or improvement or disease prevention or releasing (e.g., dietary restriction of unhealthy food and sustenance, and preventive behaviors such as safety behaviors); and those unhealthful activities and factors contribute to worsening health conditions, problems or causing illness (e.g., substance abuse such as smoking and drug-taking, and epidemic infection);

- Preventive vs. healthcare: the self-care and preventive activities that preserves or improves health conditions (e.g., HIV/AIDS-preventing sexual activities, health-improving dietary change, and allergy-avoiding food and medication-taking); and the healthcare and medical care services taken and drugs used to improve health or medical conditions (e.g., taking immunizations, screening tests, and hospitalization).

Importantly, health behaviors can also be categorized in terms of behavior subjects, i.e., whether the behaviors are made by an individual, a group, or an organization. The above discussion about health behaviors mainly refer to the behaviors of an individual or a group of individuals taking place in health-related events, processes, scenarios, and environments. *Individual health behaviors* are related to personal health-related activities, states, beliefs, mental and emotional traits and feelings, etc. *Group health behaviors* involve health-related activities undertaken by a group, and factors, relations and interactions between members in the group. *Organizational health behaviors* are typically related to the healthcare and medical care policies, laws and regulations that may normalize, shape or change individual or group's health behaviors.

In addition, today's health behaviors have been significantly transformed by the advanced socio-economic globalization, and the intelligent information, computing and communication (ICT) technology advancement-driven working and lifestyle paradigm shift to social, mobile and cloud-oriented cyberspaces and self-quantified scenarios, and the biotechnology influence on people's health determinants, conditions and problems and life quality maintenance and enhancement. These form increasing *social health behaviors*, *virtual health behaviors*, and *bio-health behaviors*.

Such social, virtual, biological and biosocial [44] health behaviors are seamlessly driven and influenced by the digitalization, virtualization, quantification, networking, embedded intelligence and personalization of traditional and existing health-related and medical activities, infrastructures, devices, and services. These big movements are fundamentally influencing and reforming our health/medical philosophies, methodologies, conceptualization, and our daily lifestyles, social interactions, entertaining and living styles and conditions, etc. [45]. These also lead to new forms of health/medical behaviors and behavioral factors; the change of conventional health contexts and environments; the evolution of living, biological, social, psychological, cultural, and economic factors and contexts; health behavior gaps, biases, imbalance, and inequality between individuals and across phases of life course, groups, regions, generations and so-

cioeconomic statuses; as well as new health-enhancing opportunities and health problems, or even threats to individual/group health and quality of life.

3.2. Medical behavior

Here *medical behaviors* refer to those actions that are related to diseases, patients, medical service providers, medicines, medical equipment, medical treatments, biomedical services, and medical professional bodies (including medical service management units, regulators and associations), etc. However, in a more broad sense, the health and medical communities may also generally refer medical behaviors to those activities relevant to health and illness, which cover health behaviors discussed in Section 3.1.

Accordingly, the *categorization and acquisition of medical behaviors* can be conducted in terms of different medical professions and behavior generators: patient behaviors, doctor behaviors, nurser behavior, tester behaviors, hospital behaviors, device usage, and professional body's behaviors, etc. Other important roles such as nutritionists, physiologist, psychologist, pharmacist, and therapist are also important generators of medical behaviors. Such medical behaviors are collectible along the medical service spectrum and disease lifecycle from diagnosis, treatment, medication and rehabilitation. Here, we count activities related to illness prevention, patient's private and public activities indirectly related to medical services but relevant to health on to the health behaviors as those are more likely general, preventative and/or self-care.

Patient behaviors refer to the ad hoc or procedural activities about whom at what time visits which service provider and accesses what medical services for what reason, and how the services are undertaken and their connections to previous services taken etc. A longitudinal sequence of patient's behaviors can be constructed by linking patient activities across different medical services and service providers. Such patient's medical behaviors can be further linked to their health behaviors before, during and after the medical services. These can form a patient behavior model, which is composed of *patient behavior elements* and behavior sequences organized per certain *patient behavior structures*, e.g.,

patient behavior graphs or networks.

Behaviors of medical service providers, including different roles of physicians, nursers, clinics and hospitals, consist of what individual and sequential activities performed on which patients, how, and why along the span of commencing and concluding the medical problems. Accordingly, we can construct different medical service provider behaviors, such as cardiologist behavior, immunologist behavior, respiratory specialist behavior, and pharmacist behavior.

Medical service behaviors consist of specific *medical service behavior elements* and are organized in terms of certain *medical service behavior structures*. For each role of medical professions, his/her medical service behaviors can be collected, constructed and organized in terms of various ways and purposes, e.g., individual patients, specific diseases, time periods, and particular groups, etc. Such medical service behaviors consist of behavior elements such as who undertakes what services on whom at what time for how long and what reasons, and the connections of this service to other services provided by the same or different service providers.

In addition, medical organizational behaviors can also be constructed to describe the activities of each medical service organization (e.g., a clinic, a hospital, a medical association, or a department unit which manages a regional or national medical businesses). *Medical organizational behaviors* record what activities undertaken at what time on what purpose and whom etc. The linkage between organizational behaviors can be built, to form sequences of medical organizational behaviors.

4. Health and medical behavior informatics

In this section, we aim to briefly discuss and outline a conceptual framework and possible opportunities of developing and applying behavior informatics for health and medical services. While health behavior and services and medical behaviors and services involve some respectively individual entities, systems, problems, goals and theories, there is a significant consideration of bridging their

gaps and fusing them from both the information integration and comprehensive evidence discovery perspective and the professional practice need perspective, as health and medical conditions and problems are interrelated and transitive. Here, we thus address their respective and integrative areas that may be better explored in terms of behaviors and behavior informatics.

4.1. Health behavior informatics

With the quantification and acquisition of various types and aspects of health behaviors as discussed in Section 3.1, health behavior informatics has great potential in acquiring and constructing health behaviors, modeling and representing health behaviors, analyzing, learning and evaluating health behaviors, and managing and applying health behaviors.

4.1.1. Health behavior acquisition and construction

Before developing and conducting behavior informatics, health behaviors must be sufficiently acquired and structurally constructed and organized. Tasks and opportunities in acquiring and constructing health behaviors may consist of collecting, processing, and structuring

- typical health behavioral data concerned in health and psychological practices, including dietary, drinking, smoking, physical, mental and lifestyle-related activities and factors;
- health longitudinal data, including protective and preventative health behaviors such as screening, vaccinations and medications;
- demographic factors, including age, race, ethnicity, gender, sexual orientation, and social class;
- personal data, including psychological, mental, emotional, feeling, belief-related data, and sexual activities;
- biological and biomedical data;

- lifestyle-related data, including habits, living and entertaining activities, and nourishment and substances taking;
- social network and social media activities, including social interactions and influence, societal and interactional activities;
- cultural, religious, and social norm-related activities;
- societal, economic, political
- mobility data, including temporal and spatial activities;
- contextual data, including institutional, inter-generational, group, and family activities;
- ecological and environmental data;
- sensor data, including wearable devices, e.g., fitbit, accessible activities and data;
- real-time activities;
- virtual behaviors in mobile applications, social networks, cloud services, and online gaming, etc.;
- change data, including circumstance change, behavior change, and habit change; and
- health outcome data, including health conditions, problems, and illness.

The above aspects of health-related data are ubiquitous, comprehensive, global, and multimodal. In practice, it is important to select the relevant data and be behavior-oriented or behavior-centric, as many aspects of the above may be general and behavior-irrelevant, although they can be valuable for general and respective health research. In addition, health behavioral data may be collected per the behavior research objectives, e.g., for specific individuals, groups, period of time, or diseases.

The collected behavioral data has to be cleaned, preprocessed, matched, transformed, and/or normalized to ensure the data quality, social and ethical quality. Possible data quality and ethical issues in health behavioral data are addressed, e.g., sparsity, imbalance, missingness, consistency, privacy and trust [5]. The output of health behavior acquisition and construction is to make the health behavioral data available, accessible, accurate and accountable for further behavior-oriented processing and use.

With the above acquired data, health behavior models, sequences and networks can be designed and constructed. This can be done from the behavioral data construction perspective, as well as by connecting to the health behavior modeling and representation.

4.1.2. Health behavior modeling and representation

Health behavior modeling and representation aims to build a formal, quantitative, structured representation of health behaviors, their relations, transitions, aggregation, and evolution and change, etc. Many specific topics and directions are possible for building behavior-centric representations, for example,

- health behavior sequence: following the sequencing method, single or multiply coupled sequences of an individual or group's health behaviors can be constructed for a period of time and by considering the ordering relationship between behaviors; behavior elements corresponding to each behavior form a behavior vector; and the behavior sequences consequently form a multi-dimensional behavior matrix for the behaviors of an individual or a group.

- health behavior graph: following the graph theory, a behavior graph can be constructed for connecting all behaviors of an individual or a group; each node may correspond to a behavior, the edge between two nodes may represent one to multiple aspects of behavior attributes, forming an attributed behavior graph; and a directed behavior graph corresponds to the ordering connections between behaviors.

- health behavior network: following certain network theories, a behavior network can be formed to connect all behaviors of an individual or a group; a node may correspond to a behavior, and an edge may refer to a behavior attribute that reflects a relationship between two behaviors, forming an attributed network; and a directed behavior network can be constructed to capture the interactive directions between behaviors from the same or different subjects.

- logical health behavior representation: with the logic theory, a logical behavior representation can be made to incorporate behavior subjects and objects as entities and the various logical relations between attributes of the same or different health behaviors.

- probabilistic health behavior representation: with probabilistic theory, a probabilistic behavior representation can be built to represent the stochastic characteristics of behaviors and the dependent relations between behavior attributes of an individual or group's behaviors.

- deep neural behavior representation: with the deep learning theory, a deep recurrent neural behavior representation can be created to embed behavior attributes and abstract hidden relations between behavior attributes and between sequential behaviors.

The output of health behavior modeling and representation is a sound organization and presentation of health behaviors and their attributes, structures, relations, and outcomes if any. This aims to make the behavioral data ready, organized and formalized for further machine-readable and computable processing and use.

4.1.3. Health behavior analysis, learning and evaluation

Building on the construction and the representations of behavioral data, *health behavior analysis, learning and evaluation* aims to create theories and methods that can analyze and learn health behavioral data to understand, interpret, identify, predict, prevent or manage health conditions, problems and

objectives, as well as evaluate the effectiveness, efficiency, impact and risk of health behaviors. Many analytic, learning and evaluation tasks and research areas may be proposed in terms of addressing different behavioral characteristics and complexities, health and disease problems and goals, and technical challenges in understanding and manipulating health behavioral data. Taking a data+domain-driven approach [46, 47, 5], examples of such tasks and areas include but not limited to:

- Health behavior determinant analysis: e.g., identifying the key behavior factors and determinants associated with the occurrence or effective intervention of a health problem, condition or illness;
- Categorization of health behaviors: e.g., categorizing, clustering and classifying health/medical behaviors into positive and negative groups, healthy and unhealthy groups, and risky and preventative groups, etc.;
- Health behavior pattern analysis: e.g., discovering healthy/unhealthy behavior patterns, or risky/preventative behavior patterns;
- Detection and early-warning of risky health behaviors: e.g., identifying and predicting habitual or incidental health behaviors or factors that may incur bad health condition or certain health problem or even disease;
- Protective health behavior discovery: e.g., discovering health behaviors that are highly protective and preventative to certain health outcomes;
- Detecting important but missing health behaviors: e.g., identifying habitually missing health behaviors that should happen and are sensitive to the occurrence or intervention of certain health problems;
- Health behavior change analysis: e.g., detecting health behavior change, quantifying the impact of behavior change on health outcomes, and identifying strategies to encourage positive change but prevent negative change;

- Modeling sequential or process-based behavior change: e.g., modeling health behavior change in terms of a process or sequence, predicting next-action;

- Hierarchical health behavior modeling: e.g., considering the hierarchical relations between health behaviors and/or factors, between people in a group, or between health problems to disclose their vertical relations and influence;

- Contrast health behavior modeling: e.g., discovering contrast (e.g., positive vs. negative, healthful vs. unhealthful) behavior factors and patterns between individuals, groups or health conditions;

- Convertible health behavior modeling: e.g., identifying those risky and negative health behaviors, behavior factors or patterns which can be converted to preventative and positive conditions or states; and vice versa;

- Group health behavior analysis: e.g., analyzing collective health behavior patterns in a group, comparing health behaviors across groups, and analyzing contrast behaviors across groups;

- Modeling relations between multi-aspect behavior factors: e.g., building a universal profile of health behaviors by connecting multiple aspects of factors, modeling the relations between behavior factors and behaviors from multi-aspects, and conducting various behavior analysis on top of the relational multi-aspect behavior factors;

- Modeling social health behaviors: e.g., modeling patterns and anomalies in health-related individual or group social network and social media activities; modeling social relationships, social mood, and social influence of unknown peers' health behaviors on target individuals or groups;

- Predicting health outcomes of health behaviors: e.g., estimating the likelihood of incurring certain health outcomes (e.g., health condition wors-

ening or appearance of certain illness) due to some risky health behaviors or behavior factors;

- Modeling health behavior impact within a context: e.g., valuating and estimating the social and economic impact of undertaking certain health behaviors, especially within a certain mental, sentimental, environmental, and physical context;

- Modeling the effectiveness of health behavior interventions: e.g., quantifying and evaluating the effectiveness of applying specific health intervention actions or processes to changing or converting an individual/group's specific health behaviors or health outcomes;

- Predicting next-best health behavior intervention: e.g., estimating and recommending next-best health interventions or intervention strategies based on modeling the evolution of and their relations between health behaviors, contexts and health outcomes.

The outcomes of health behavior analysis, learning and evaluation include an in-depth understanding of intrinsic characteristics, relations, structures, and dynamics of health behaviors and their relationships to health conditions and outcomes. Possible benefits are multifaceted, e.g., disclosing useful and insightful internal patterns, clustering, trends, exceptions, risk and change in health behaviors; positive and negative relations and influence of multi-aspect health behaviors on health outcomes; sound evidence and indication for effective intervention, transformation, and management of negative health behaviors and their risk and impact.

4.1.4. Health behavior management and applications

Health behavior management and applications is to apply health behavior informatics for better understanding, education, intervention, improvement, and decision-making of health services and quality of life and health care. Centered on health services and health care, health behavior management and applications enable individuals, groups, and organizations to select, recommend,

optimize, transform or intervene health behaviors and behavior determinants for better objectives and outcomes. Diverse health behavior applications are possible, for example,

- categorization of health behaviors and behavior actors (including individuals, groups and organizations) into positive/negative, healthy and unhealthy, or reckless/protective behaviors patterns and behavior clusters;
- identification of discriminant behavior factors and determinants of health conditions and outcomes by analyzing complex relations between behavior factors and filtering noisy and redundant factors;
- discovery of risky behavior factors and behavior patterns or abnormal behavior patterns that may be associated or correlated with certain health problems or outcomes or illness;
- evaluation and quantification of behavior prevalence and impact on health and medical treatment and performance;
- identification of target individuals and groups whose health problems or outcomes may likely be transferred from negative to positive, or from risky to healthful conditions;
- identification of habitual unhealthy behaviors in certain groups and individuals and the recommendation of interventions to change key factors and determinants for effective transformation;
- discovery of better strategies for maintaining, attaining and regaining healthy behaviors and enabling positive health behavior change[48];
- recommendation of optimal, next-best, or personalized interventions on target health behavior and health condition change;
- prediction of group-oriented (including region, season, and age group-oriented) burst of health problems and recommendation of target intervention strategies;

- identification of key external factors (including biological, cultural, environmental, societal and ecological factors) that are highly associated with certain health problems and outcomes.

Accordingly, different health behavior management systems may be built to collect, analyze, evaluate, manage health behaviors of those targeted individuals, groups and organizations. Health behavioral data and evidence-based periodical technical reports can be generated to show the statistical and analytical results of health conditions, problems, and outcomes. Target experimental design and trials of health behavior interventions can be made based on longitudinal data analysis and evidence discovery. More active, personalized and real-time intervention on health problems and health behavior change, and engagement of individuals and groups are possibly informed by the results of health behavior informatics.

4.2. Medical behavior informatics

Following the framework of behavior informatics, *medical behavior informatics* consists of major research areas and application opportunities in medical behavior acquisition and construction, medical behavior modeling and representation, medical behavior analysis, learning and evaluation, and medical behavior applications and management. Many topics and areas discussed about health behavior informatics in Section 4.1 can be cloned or projected to build medical behavior informatics. Medical behavior informatics covers behavior informatics for much broader stakeholders, more hierarchical behavior subjects and objects, more specialized behavior types, and more connected behavior relations; while health behavior informatics may involve much broader aspects of data. Here, rather than having an extensive discussion about areas and opportunities of each of those directions, we highlight those specific to medical businesses and data-driven and personalized medicine.

4.2.1. Medical behavior acquisition and construction

Medical behaviors may be collected and organized in terms of

- Patient's behaviors taken place in medical service provision places, including details of accessing services, reasons, connected other services, hospital admission and readmission data, and out-of-hospital medical services;
- Medical service provider's behaviors for particular patients, diseases, service types, or groups etc.;
- Medical equipment and service usage data, including system log about when what equipment is used, and the actual recording/imaging and media of the service content and on whom the service is done by whom etc.;
- Treatment data, including what treatment and medication are made on whom by whom for how long and how, etc.;
- Pharmaceutical service data; and
- Other relevant medical behavioral data, e.g., the usage of auxiliary medical services, emergency service data.

With the above medical behavioral data collected, we can build a medical behavior sequence for each patient, service provider, disease, treatment, group, or organization etc. By matching the relevant medical services, we can build medical behavior graphs or networks for a patient, service provider, disease, group or organization, which connects the behaviors of multiple related actors for a certain period of time. These make medical behaviors ready for further analysis, learning, evaluation, and applications.

4.2.2. Medical behavior modeling and representation

Medical behavior modeling and representation is to formalize, match, aggregate, structure, and organize medical behavioral data for a quantitative and structured representation of medical behaviors, their elements, structures, relations, and dynamics. All the topics discussed in Section 4.1 about health behavior modeling and representation are convertible and customizable for modeling and representing medical behavioral data, except that more effort has to be made on organizing and representing medical imaging data and genomic data.

- Medical imaging data representation: e.g., discriminative imaging feature extraction, video compression, and compressed video-based access and analysis;
- genomic data representation: e.g., gene sequencing for efficient editing and analysis;
- Multimodal medical imaging representation: e.g., alignment and feature construction of PACS, CT and fMRI imaging data for multimodal imaging analysis;
- Multi-modal medical behavior representation: e.g., matching and alignment of multimodal imaging data with clinical transactions stored in hospital information systems for unified behavior representation; and
- Biological, medical and social behavior-combined representation: e.g., the construction of a universal patient behavior profile by aligning patient's biological behavior, medical behavior with social behavior in social networks.

As a result of medical behavior modeling and representation, various or specific medical behavioral data is constructed and formalized, which is made machine readable and computable for further analyses and applications.

4.2.3. Medical behavior analysis, learning and evaluation

Medical behavior analysis, learning and evaluation aims to build theories and methods that can explain, identify, predict, prevent, evaluate, optimize and intervene medical behavior-related problems, conditions, and outcomes and make medical services more effective, efficient, personalized and intelligent for encouraging more effective, positive and healthful medical behavior and behavior change. Most of the topics discussed in health behavior analysis, learning and evaluation can be customized, converted and applied on medical behaviors, which we do not repeat here. Some of additional opportunities include:

- Cost-effective medical behavior pattern: e.g., identifying unnecessary repeating medical services, repeated or similar treatments and medications, and unnecessary readmissions;
- Discovering unnecessary but expensive medical services: e.g., identifying unnecessary screening, such as MRI check, CT test, or appointments with specialists;
- Multimodal medical behavior analysis: e.g., identifying unnecessary similar imaging tests (e.g., MRI and CT) and suggesting single suitable medical test;
- Sequential analysis of disease change: e.g., by constructing and analyzing sequence of imaging data for a patient taken during the disease appearance period to identify disease change and the effectiveness of treatments;
- Associated group's medical behavior analysis: e.g., by aligning family members' medical behaviors to identify unnecessary screening tests on some members (who may took unnecessary medical services while accompanying the others in health/medical trouble);
- Discovering more/less effective medical services: e.g., benchmarking the same category of medical services (including test, treatments and medications) to identify more and less effective service providers or recipients;
- Detecting mismatches between services and diseases: e.g., discovering those medical services (including tests, treatments and medications) that do not have effective impact on some patients or disease treatments, or unusual patient-provider relations (e.g., fraud);
- Recommending next-best treatments: e.g., modeling the evolution of medical outcomes of sequential treatments to recommend the next most suitable treatments or the next suitable timeframe for treatment;

- Medical behavior change analysis: e.g., analyzing the effect of patient's medical behavior change to encourage healthful behavior change or prevent harmful change; and

- Cross health and medical behavior analysis: e.g., aligning health behaviors with medical behaviors of particular patients or disease holders to generate a multifaceted view or profile of patient's behaviors.

The output of medical behavior analysis, learning and evaluation include an deep understanding, insight and indication of high vs. low-performing of medical services, cost-effective vs. cost-ineffective medical services, and sound indication and evidence for optimizing medical behavior change, treatment effect, and resource usage and planning etc.

4.2.4. Medical behavior applications and management

Medical behavior applications and management are very promising, similar opportunities to those discussed for health behavior management are also convertible to medical behaviors, in addition to other opportunities for achieving better medical objectives and outcomes. Examples are

- medical resource saving and planning optimization by identifying unnecessary medical checks, treatments and medications;

- more efficient guidance and education of applying for more cost-effective medical services and assigning/referring patients to necessary and effective medical services;

- benchmarking the quality of medical services;

- identifying medical service fraud and anomalies, behavior disorder and behavior abnormality;

- discovering healthier medical behaviors and opportunities of transforming medical behaviors;

- supporting behavior therapy;

- enabling more active, real-time, on-demand, personalized and sequential medical services; and

- supporting cross-health and medical behavior medicine by aligning and analyzing health and medical behaviors of a patient and his/her service providers.

4.3. Integrative health and medical behavior informatics

In practice, it is doable and necessary to integrate the outcomes of health behavior informatics and medical behavior informatics for understanding, analyzing, improving and managing health and medical problems and outcomes as a systematic and holistic approach and goal. Often, it may not be realistic, and may incur biased view, to just focus on one side or another. The base of integrative health and medical behavior informatics is to integrate health behavioral data with medical behavioral data.

Further, health and medical behavior management systems can be built, which can be composed of health and medical behavioral data as well as ordinary health and medical transactions and imaging data; and functional modules for behavioral sequencing, behavioral management, treatment management, medication management, and interfaces for intervening health and medical behaviors. Visualization tools can be incorporated to visualize health and medical behavior profile, behavior intervention effect on health and medical outcomes, etc.

5. Related work

In this section, we discuss the connections between health and medical behavior informatics and the existing health and medical behavior research. Figure 2 summarizes some major research areas in health and medical behavior informatics and their connections to some of existing areas.

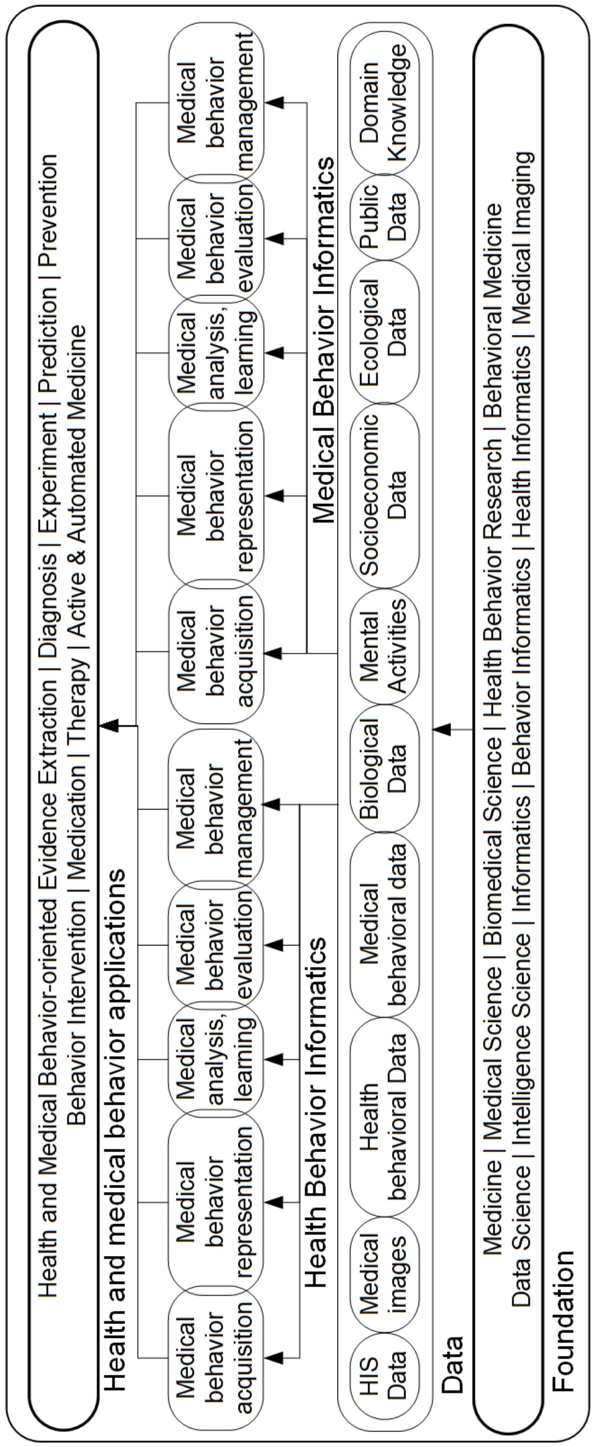

Figure 2: Research map of health and medical behavior informatics.

5.1. Connection to health behavior research

With health behaviors, classic health behavior research has introduced several general models and theories for explaining key health behavior determinants. Among them, the *health belief model* [17] is probably the most classic and popular one explored widely in the health communities. With a qualitative process and a certain level of belief in action-taking, the model explains and predicts a health behavior to be taken so as to prevent or control a health problem. Other models attracted interest in the health and psychology communities include protection motivation theory [49], self-determination research [50], and social cognitive theory (e.g., self-efficacy mechanism [51]). These models often focus on common factors and determinants across health behaviors and in different populations. There have been many variants developed on top of these models up to date [39].

The main difference between health behavior research in health and health behavior informatics lies in their different motives, perspectives and approaches. Health behavior informatics builds behavior understanding and discovers behavior intelligence [1] on the basis of health behavioral data and informatics theories and approaches. One way to connect health behavior research to health behavior informatics is to view health behavior informatics as the advanced stage of health behavior research, which is data-driven, evidence-based, and informatics-enabled, as well as active, personalized, holistic, and intelligent.

5.2. Connection to behavioral medicine

Behavioral medicine [16] is a concept proposed about 40 years ago, which advocates the interdisciplinary and translational methodology of integrating behavioral science, social science, and psychological science with biomedical science to understand, diagnose, prevent, intervene, resolve and manage health and medical problems. Behavior medicine values the roles of managing and intervening behaviors for improving health and well-being, and has attracted wide interest in health and medical domains as well as involve various health professions from psychologist, health carer to physician, nutritionist, and social

worker. The above brief review indicates that the so-called behavioral medicine takes similar approaches and serves similar goals as health behavior research, or builds on health behavior research.

In contrast, medical behavior informatics is centered on medical behavioral data (which is extracted from medical services) and takes informatics-driven approaches for evidence-based understanding, evaluation, discovery, intervention and management. With the availability of data science, medical imaging, and intelligence science, medical behavior informatics can significantly improve and upgrade behavioral medicine toward personalized, active and intelligent medicine.

5.3. Connection to health/medical informatics and medical imaging

The value of combining behavior research, health research, and medical research with IT technology has been widely recognized in both health and medical communities and technological communities (e.g., [52]). Accordingly, several concepts and approaches have been explored, e.g., health informatics [53], medical informatics [54][1], medical imaging [55], medical image analysis [56], and various 'omics technologies.

While informatics approaches serve as the mutual means for health/medical informatics and medical imaging and image analysis and health and medical behavior informatics, health and medical behavior informatics is centered on behavioral data and aims for discovering behavior-oriented insight and intelligence, and enabling behavior change-driven intervention and management. Hence, health and medical behavior informatics focus on the kernel stone of health and medicine, i.e., behavior-centric health/medical problems, and are more actionable [57].

[1] The concepts of health informatics and medical informatics were originally introduced by researchers in health and medical communities, their focus was less informatics-centered, and these two concepts are somehow exchangeable.

6. Prospects

Here, we briefly explore some prospects of data-driven personalized health and medicine with health and medical behavior informatics.

With the wide recognition of data science and artificial intelligence in today's scientific and commercial agenda and activities, in particular, the advancement of deep analytics and deep learning [58], a new-generation analytics and applications of health and medical data becomes promising. Deep data analytics, deep behavior analytics, and integrating such deep analytics into intelligent health and medical data and behavior understanding, problem resolution, device enhancement, and evidence-based management and decision-making become a major trend in health and medical research. This has also become an increasingly focused area in the research agenda of data science and artificial intelligence. Data science and technologies enable a new-generation of artificial intelligence, is driving the transformation of science, technology and economy [5]; it is certainly also driving the transformation of intelligent, automated, and personalized health/medical services, decision-making, and health and well-being.

With the above context, below, we share some view of several promising directions of health behavior informatics and medical behavior informatics in the health and medical domains: health and medical data science, data-driven experimental medicine, data-driven personalized medicine, and active and automated medicine.

Health/medical data science The fast adoption of embedded and wearable devices, IoT devices, smart home applicants, broadband Internet services, multimedia-supporting Internet, wireless networks and mobile services, and diverse health and medical sensors in our daily working, living, studying, entertaining, traveling process collect ubiquitous aspects of our health and medical data, behaviors, and conditions. The recorded human body activities, human behaviors, lifestyle activities, etc. can be shared with or connected to the professionally collected health and medical data by medical and healthcare ser-

vice providers. These form increasingly bigger and valuable *health/medical big data*, and trigger the emergence of *health/medical data science*. The synergy of health/medical data science with medicine science, behavior informatics, and broad intelligence science, is fundamentally translating the health and medical sciences into a new generation, enabling active (on-the-fly) health/medical management and intervention, personalized healthcare and medicine, and even automated medicine.

Data-driven translational and experimental medicine *Experimental medicine* [59] has been widely explored in training of physicians and medical practice, which use medicines as clinical probes to identify or verify a target health problem, and develop effective medication and treatment of diseases. Taking an interdisciplinary and data and evidence-driven approach, *translational medicine* aims to develop new and effective medicines, medical devices, and treatments for new and better clinical outcomes. To this end, we have to synergize data-driven discovery in health and medical data and behaviors (including behavior informatics, medical imaging analysis, and 'omics techniques) with the experimental health and medicine, and behavioral health and medicine.

Data-driven personalized medicine *Personalized medicine*, or *precision medicine* [60], aims to customize medicine, medications and medical interventions for individual patients or specific diseases. Its original focus has been on associating individual's genomic information and conditions with medicines for more effective treatment. The collection and integrative computing, analysis, learning and evaluation of massive clinical data, genomic data, health behaviors, and external data have the potential of customizing medications and treatments for individual patients or diseases with better effect, i.e., data-driven personalized medicine, since genomics may not be the only or main trigger of many health and medical problems.

Active and automated medicine With the data science capabilities of active and intelligent acquisition, processing, analysis, learning and recommendation of health and medical data, active and automated medicine becomes possible. Automated medicine may replace most of ordinary medical services

in the future. Active and automated medicine enables an e-doctor (wearable, embedded in smart home, or virtual doctor online) attached to a person to actively collect and analyze the person's health behaviors taking place within his/her environment, health conditions collected by the wearable devices, and relevant health/medical records from his visited medical service providers, and intelligently diagnose, discover, predict, prevent and intervene health/medical problems for smarter health enhancement, illness prevention, self-medication, personalized medical treatment, and tailored recovery.

A promising automated medicine scenario is as follows. A patient have wearable health/medical sensors (a wearable e-doctor) embedded in her e-skin, which senses, diagnoses and evaluates her healthy parameters and body conditions in real time. When it is necessary, the wearable e-doctor connects and accesses the person's health behaviors and records stored in her smart home devices, e-hospitals and visited hospital digital libraries. The relevant health and medical data is then analyzed and alerted by cloud-based e-health analyzers, which are data/behavior analytics and machine learning algorithms trained on massive health/medical data. The analytical results are then sent back to patient's wearable e-doctor which is displayable at her smart home screens or tablets with alerts, suggested prescriptions and a suggested intervention plan. The patient can connect to online doctors to verify the personal e-doctor's recommendation before implementing the interventions. As a result, the patient's health condition is monitored, diagnosed, analyzed, and treated in real time, autonomously, personalized, and effectively.

In conclusion, we firmly believe that the marriage of health/medical science with behavior informatics, i.e., health and medical behavior informatics, building on the advancement of data science and intelligence science, will make health/medical behaviors really matter by discovering their value, insight and intelligence for more active, tailored, personalized, real-time, and automated health care and medicine, and play an important role in translational medicine.

Acknowledgement

This work is sponsored in part by the Australian Research Council Discovery Grant (DP190101079).

References

[1] L. Cao, Behavior informatics to discover behavior insight for active and tailored client management, in: KDD'2017 invited talk, 2017, pp. 15–16.

[2] L. Cao, Kdd2018 tutorial on behavior analytics: methods and applications (2018).
URL http://203.170.84.89/~idawis33/DataScienceLab/wp-content/uploads/2018/08/Tutorial-Proposal-for-KDD2018-3.pdf

[3] L. Cao, Aaai2019 tutorial on behavior analytics: methods and applications (2019).
URL http://203.170.84.89/~idawis33/DataScienceLab/publication/Behavior_analytics-tutorial-slides.pdf

[4] E. B. Fisher, M. L. Fitzgibbon, R. E. Glasgow, D. Haire-Joshu, L. L. Hayman, R. M. Kaplan, M. S. Nanney, J. K. Ockene, Behavior matters, American Journal of Preventive Medicine 40 (2011) 15–30.

[5] L. Cao, Data Science Thinking: The Next Scientific, Technological and Economic Revolution, Springer International Publishing, 2018.

[6] L. Cao, In-depth behavior understanding and use: The behavior informatics approach, Inf. Sci. 180 (17) (2010) 3067–3085.

[7] L. Cao, P. S. Yu, Behavior Computing: Modeling, Analysis, Mining and Decision, Springer, 2012.

[8] L. Cao, Y. Zhao, C. Zhang, H. Zhang, Activity mining: From activities to actions, International Journal of Information Technology and Decision Making 7 (2) (2008) 259–273.

[9] C. Wang, L. Cao, Modeling and analysis of social activity process, in: L. Cao, P. Y. (eds.) (Eds.), Behavior Computing: Modeling, Analysis, Mining and Decision, Springer, 2012, pp. 21–35.

[10] S. Herath, M. T. Harandi, F. Porikli, Going deeper into action recognition: A survey, Image Vision Comput. 60 (2017) 4–21.

[11] L. Cao, Coupling learning of complex interactions, Inf. Process. Manage. 51 (2) (2015) 167–186.

[12] N. Barberis, R. Thaler, A survey of behavioral finance, Vol. 1 of Handbook of the Economics of Finance, Elsevier, 2003, pp. 1053–1128.

[13] Z. Zheng, W. Wei, C. Liu, W. Cao, L. Cao, M. Bhatia, An effective contrast sequential pattern mining approach to taxpayer behavior analysis, World Wide Web 19 (4) (2016) 633–651.

[14] W. Wei, J. Li, L. Cao, Y. Ou, J. Chen, Effective detection of sophisticated online banking fraud on extremely imbalanced data, World Wide Web 16 (4) (2013) 449–475.

[15] S. Gong, T. Xiang, Visual Analysis of Behaviour - From Pixels to Semantics, Springer, 2011.

[16] G. E. Schwartz, S. M. Weiss, Behavioral medicine revisited: An amended definition, Journal of Behavioral Medicine 1 (3) (1978) 249–251.

[17] M. H. B. (ed.), The health belief model and personal health behavior, Vol. 2 of Health education monographs, Society for Public Health Education, San Francisco, 1974, p. 324473.

[18] D. B. Neill, W.-K. Wong, Kdd'2009 tutorial on event detection (2009). URL `https://www.cs.cmu.edu/~neill/papers/eventdetection.pdf`

[19] L. Cao, Y. Ou, P. S. Yu, Coupled behavior analysis with applications, IEEE Trans. Knowl. Data Eng. 24 (8) (2012) 1378–1392.

[20] L. Cao, Y. Zhao, C. Zhang, Mining impact-targeted activity patterns in imbalanced data, IEEE Trans. on Knowledge and Data Engineering 20 (8) (2008) 1053–1066.

[21] Y. Zhao, H. Zhang, L. Cao, C. Zhang, H. Bohlscheid, Mining both positive and negative impact-oriented sequential rules from transactional data, in: Advances in Knowledge Discovery and Data Mining, 13th Pacific-Asia Conference, PAKDD 2009, Bangkok, Thailand, April 27-30, 2009, Proceedings, 2009, pp. 656–663.

[22] L. Cao, Y. Zhao, F. Figueiredo, Y. Ou, D. Luo, Mining high impact exceptional behavior patterns, in: Emerging Technologies in Knowledge Discovery and Data Mining, PAKDD 2007, International Workshops, Nanjing, China, May 22-25, 2007, Revised Selected Papers, 2007, pp. 56–63.

[23] J. Yin, Z. Zheng, L. Cao, Y. Song, W. Wei, Efficiently mining top-k high utility sequential patterns, in: ICDM'2013, 2013, pp. 1259–1264.

[24] J. Yin, Z. Zheng, L. Cao, Uspan: an efficient algorithm for mining high utility sequential patterns, in: KDD'12, 2012, pp. 660–668.

[25] J. Shao, J. Yin, W. Liu, L. Cao, Mining actionable combined patterns of high utility and frequency, in: DSAA'2015, 2015, pp. 1–10.

[26] L. Cao, Behavior informatics and analytics: Let behavior talk, in: ICDM'2008 workshop, 2008, pp. 87–96.

[27] C. Wang, L. Cao, C. Chi, Formalization and verification of group behavior interactions, IEEE Trans. Systems, Man, and Cybernetics: Systems 45 (8) (2015) 1109–1124.

[28] L. Cao, T. Joachims, C. Wang, É. Gaussier, J. Li, Y. Ou, D. Luo, R. Zafarani, H. Liu, G. Xu, Z. Wu, G. Pasi, Y. Zhang, X. Yang, H. Zha, E. Serra, V. S. Subrahmanian, Behavior informatics: A new perspective, IEEE Intelligent Systems 29 (4) (2014) 62–80.

[29] L. Cao, Y. Ou, P. S. Yu, G. Wei, Detecting abnormal coupled sequences and sequence changes in group-based manipulative trading behaviors, in: KDD, 2010, pp. 85–94.

[30] L. Cao, P. S. Yu, V. Kumar, Nonoccurring behavior analytics: A new area, IEEE Intelligent Systems 30 (6) (2015) 4–11.

[31] L. Cao, X. Dong, Z. Zheng, e-nsp: Efficient negative sequential pattern mining, Artif. Intell. 235 (2016) 156–182.

[32] Y. Yue, H. M. Le, Icml2018 tutorial on imitation learning (2018). URL https://sites.google.com/view/icml2018-imitation-learning/

[33] W. Cao, L. Cao, Financial crisis forecasting via coupled market state analysis, IEEE Intelligent Systems 30 (2) (2015) 18–25.

[34] Y. Song, L. Cao, X. Wu, G. Wei, W. Ye, W. Ding, Coupled behavior analysis for capturing coupling relationships in group-based market manipulations, in: KDD'12, 2012, pp. 976–984.

[35] L. Cao, C. Luo, C. Zhang, Developing actionable trading strategies for trading agents, in: IAT'2007, 2007, pp. 72–75.

[36] L. Cao, T. He, Developing actionable trading agents, Knowl. Inf. Syst. 18 (2) (2009) 183–198.

[37] Y. Zhao, H. Zhang, L. Cao, C. Zhang, H. Bohlscheid, Combined pattern mining: From learned rules to actionable knowledge, in: Australasian AI'2008, 2008, pp. 393–403.

[38] Y. Zhao, H. Zhang, S. Wu, J. Pei, L. Cao, C. Zhang, H. Bohlscheid, Debt detection in social security by sequence classification using both positive and negative patterns, in: ECML/PKDD'2009, 2009, pp. 648–663.

[39] M. Conner, P. Norman, Health behaviour: Current issues and challenges, Psychology & Health 32 (8) (2017) 895–906.

[40] K. Glanz, F. M. Lewis, B. K. Rimer, Health Behavior and Health Education: Theory, Research and Practice (2nd ed.), Jossey-Bass, San Francisco, 1997.

[41] D. S. e. Gochman, Handbook of Health Behavior Research (Volumes 1-4), Plenum, New York, 1997.

[42] S. V. Kasl, S. Cobb, Health behavior, illness behavior, and sick-role behavior, Archives of Environmental Health 12 (246266) (1996) 531541.

[43] B. Spring, A. C. Moller, M. J. Coons, Multiple health behaviours: Overview and implications, Journal of Public Health 34.

[44] S. E. Short, S. Mollborn, Social determinants and health behaviors: Conceptual frames and empirical advances, Current opinion in psychology 5 (2015) 78–84.

[45] L. Cao, Data science: A comprehensive overview 50 (3) (2017) 1–42.

[46] L. Cao, P. S. Yu, C. Zhang, Y. Zhao, Domain Driven Data Mining, Springer, 2010.

[47] L. Cao, Domain driven data mining: Challenges and prospects, IEEE Trans. on Knowledge and Data Engineering 22 (6) (2010) 755–769.

[48] P. Sheeran, W. M. Klein, A. J. Rothman, Health behavior change: Moving from observation to intervention, Annual Review of Psychology 68 (2017) 573–600.

[49] J. E. Maddux, R. WRogers, Protection motivation and self-efficacy: A revised theory of fear appeals and attitude change, Journal of Experimental Social Psychology 19 (1983) 469–479.

[50] E. L. Deci, R. M. Ryan, Handbook of Self-determination Research, University Rochester Press, 2004.

[51] A. Bandura, Self-efficacy mechanism in human agency, American Psychologist 37 (1982) 122–147.

[52] D. J., K. A., E. P., A new frontier: Integrating behavioral and digital technology to promote health behavior, The Behavior Analyst 38 (2014) 124.

[53] Wikipedia, Health informatics (2019).
URL https://en.wikipedia.org/wiki/Health_informatics

[54] R. Greenes, E. Shortliffe, Medical informatics: An emerging academic discipline and institutional priority, Journal of the American Medical Association 263 (1990) 1114–1120.

[55] Wikipedia, Medical imaging (2019).
URL https://en.wikipedia.org/wiki/Medical_imaging

[56] P. M. de Azevedo-Marques, A. Mencattini, M. Salmeri, R. M. R. (eds), Medical Image Analysis and Informatics: Computer-Aided Diagnosis and Therapy, CRC Press, 2017.

[57] L. Cao, Actionable knowledge discovery and delivery, Wiley Interdiscip. Rev. Data Min. Knowl. Discov. 2 (2) (2012) 149–163.

[58] Y. LeCun, Y. Bengio, G. Hinton, Deep learning, Nature 521 (7553) (2015) 436–444.

[59] C. Bernard, An Introduction to the Study of Experimental Medicine, Dover Publications, 1957.

[60] M. A. Hamburg, F. S. Collins, The path to personalized medicine, New England Journal of Medicine 363.