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Commentary

Cognitive informatics in biomedicine and healthcare

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1. Introduction: Role of cognition in biomedical informatics

We are at a turbulent, yet exciting, phase in healthcare – *turbulent*, as the transformations in healthcare practice have been driven by paradigmatic shift toward the use of health information technology (HIT), both as a result of necessity and federal mandates; *exciting*, as such transformations have highlighted the central role of cognitive and behavioral sciences in developing usable systems that can provide high quality patient care. While there is a bright future, in terms of opportunities for researchers and practitioners who seek to engage in cognitive science research, it is also important to *reflect on past research* – to understand (a) the historical context and foundations of the development of cognitive research in biomedical informatics, (b) the theories, constructs and frameworks that drive the current research, and (c) the potential directions for future research. Within this focus, this special communication provides a broader context of the cognitive and behavioral research on HIT in biomedical informatics. In addition, we have also created a *virtual issue* of the *Journal of Biomedical Informatics* (JBI) that will provide a snapshot of the research that has been published in JBI pertaining to cognitive and social science research (see Refs. [1–57]).

Cognitive science is an interdisciplinary field that draws from psychology, computer science, linguistics, philosophy and anthropology to understand human activities including reasoning, decision-making and problem solving. Principles from cognitive science have been applied for studying the usability of medical devices and interfaces [55]; developing training, educational interventions and guidelines [39]; streamlining and improving workflow and clinical processes [29]; and for understanding the process of clinical judgment, reasoning and decision-making [58]. In summary, cognitive science provides a viable mechanism to inform our understanding in technology-rich clinical environments, and represents an important component of biomedical informatics [59]. Additionally, cognitive research has been a key to shaping and structuring the use of HIT, adapting to the various needs of the clinical environment.

Cognitive informatics (CI), by extension, is an interdisciplinary field comprising of cognitive and information sciences, specifically focusing on human information processing, mechanisms and processes within the context of computing and computer applications [60,61]. The focus of CI is on understanding work processes and activities within the context of human cognition and the design of interventional solutions (often engineering, computing and information technology solutions) that can improve human activities. Within the context of biomedical informatics, CI plays a key role – both in terms of understanding, describing and predicting the nature of clinical work activities of its participants (e.g., clinicians, patients, and lay public) and in terms of developing engineering and computing solutions that can improve clinical practice (e.g., a new decision-support system), patient engagement (e.g., a tool to remind patients of their medication schedule), and public health interventions (e.g., a mobile application to track the spread of an epidemic).

Theoretical and methodological approaches from cognitive science have informed the design and evaluation of HIT, and also in understanding and improving the efficiency of healthcare providers. Original research in CI has drawn significantly from cognitive science topics related to comprehension, problem solving and decision. Cognitive research evolved from Newell and Simon's [62] conceptualizations of individual "thought" and "mental processes", and "human problem solving." Original studies of problem solving introduced protocol-analytic approaches [63], human information processing theories that, consequently, laid the foundation for the discipline of human computer interaction (HCI). Methods such as verbal think-aloud have been extensively used in CI research, and have been influential in developing our understanding regarding medical problem solving and decision-making and reasoning. Similarly, Kintsch's [64] research on text comprehension has been instrumental in shaping CI research related to reasoning and decision-making in healthcare.

Recognition of the role of cognition in biomedical informatics has shown slow, but positive, growth. While the role of cognition in characterizing the nature of clinical decision-making, judgment and reasoning has been well acknowledged [65,66], the prevalence of cognitive science research in mainstream informatics literature did not occur until the late 1990s. One of the key contributions toward the integration of cognitive science and biomedicine came in 1989 with a book that assembled key papers in biomedicine from the fields of cognitive psychology, linguistics, computer science, anthropology and philosophy [67]. The book provided an

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early scientific foundation of cognition science for investigations in biomedical modeling.

"Cognitive science" as a category of submission at the flagship American informatics conference, AMIA, did not occur until 1996. Internationally, such interest developed a few years later (with recognition at, for example, the European Artificial Intelligence in Medicine conference and the journal *AI in Medicine*). Though the *Journal of the American Medical Informatics Association* (JAMIA) published papers related to cognition (see e.g., [68,69]) as early as the late nineties, cognition was still considered as being on the periphery of informatics research. In our previous work [70], we conducted an informal evaluation of cognitive studies across three leading informatics journals over two time periods (2001–2005 and 2006–2010): *Journal of Biomedical Informatics, Journal of the American Medical Informatics Association* and the *International Journal of Medical Informatics*. Based on a keyword search (using common terms such as cognition, cognitive decision support, usability testing and human factors), it was found that the second time period (2006–2010) had 70% more cognition related terms than the first. As the authors argued, while not conclusive, this points toward a growth of cognitive research in recent years [70].

Additionally, the Institute of Medicine (IOM) reports of 1999 and 2011 [71,72], highlighting the role of human cognition, accelerated the growth of cognitive science research in informatics. Influential research papers (see e.g., [73]) on the cognitive underpinnings of physician behavior further illustrated the importance of this field. More recently, the federal mandates regarding health information technology (HIT) adoption and use has reinvigorated cognitive informatics research, leading to new avenues and research directions.

As previously mentioned, our focus is on characterizing the growth, development and translation of research pertaining to cognition in biomedical and health informatics that was published in the *Journal of Biomedical Informatics* between January 2001 (when *Computers and Biomedical Research* (CBR) was reborn as JBI) and March 2014. This analysis emphasizes JBI because we performed the work for a JBI virtual issue consisting of articles previously published in the journal. Other informatics journals and conferences have published cognitive informatics papers in the same time period, but JBI has published an especially large portion of the cognitive papers since its debut in 2001, and those in JBI give a reasonable sense of general trends in the field. Since 2001, JBI has included research articles, methodological review articles, and general review articles that discussed human or team cognition, and its role in informatics. In the virtual issue that accompanies this article, we have collected a set of 57 papers. Additionally, given the breadth of topics that have been covered, we have categorized these papers along multiple cognitive dimensions. These dimensions will help in characterizing the nature of research on cognition in biomedical informatics, current research foci, changes occurring over the past decade, and directions for future research.

2. Method

We begin by describing the process used to select the research and review articles, including the inclusion criteria, the extraction of relevant data from these articles, and their categorization into the cognitively relevant categories.

2.1. Search process and inclusion criteria

We used a manual search process where we evaluated each article that was published in JBI between January 2001 and March 2014 that focused on topics related to cognition. Specifically, our definition of cognition included two aspects of cognition in healthcare contexts: (a) thinking, reasoning or decision-making, and (b) interaction with technology, collaborators or the social environment. Within these topical boundaries, we included articles with a research focus, methodological review articles and general review articles for our analysis. Editorials, commentaries and book reviews were not included. To categorize the papers, we used a broad framework that accounts for individual cognitive activities (e.g., comprehension, reasoning and decision-making), cognitive activities that are shared among a team (e.g., communication, coordination and interactions) and cognitive underpinnings of human interaction with computer systems or medical devices (e.g., usability).

2.2. Data extraction and synthesis

Based on the definitions, article selection was conducted in two phases. First, we identified articles that fit into one or more of the frameworks of cognition based on the title, abstract and keywords. Second, two researchers reviewed each of these articles. A final set of fifty-seven ($n = 57$) articles that fit our framework definitions was selected for further analysis. Of these, thirty-eight ($n = 38$) were research articles and the rest ($n = 19$) were review articles. We followed a similar procedure in reviewing and categorizing each of the articles (with minor differences between research and review articles; details are provided below).

2.2.1. Research articles

Each research article was read and a short summary was developed. This narrative summary included the main focus of the article, themes that were investigated, and the main findings from the study. Next, each article was categorized along multiple dimensions (see Table 1 for a full list).

The *geographical location* of the first author of the article was recorded. In the research articles selected for this review, this often coincided with the study site. The purpose of this classification was to identify the origin/source of the articles. The *cognitive framework* dimension was used to describe the foundational aspect of cognition that was used: comprehension, decision-making, distributed cognition, errors, training or usability evaluation. We provide a brief overview of each of these categories. Articles that discussed how individuals or groups perceived, comprehended and used information from the clinical environment or health IT were classified under *comprehension*. Studies on medical *decision-making*, both within clinical contexts (e.g., diagnosis, use of tools for decision support) and outside (e.g., lay public's decision-making under various public health situations), were classified as such. *Distributed cognition* encompassed articles that described the distributed nature of clinical activities, both among individuals and teams. Articles that focused on cognitive underpinnings and factors that led to *errors* were classified as such. *Usability* studies captured the design or evaluation of the cognitive aspects of health IT or decision support user interfaces. Articles that did not fall into any of these categories were grouped into a generic *other* category (we also categorized articles related to training and education within this category).

The *study type* dimension was used to classify the nature of study: experimental or naturalistic, with experimental studies referring to those conducted in laboratory or other controlled settings, and naturalistic studies conducted in real-world settings (e.g., clinics or hospital units). Similarly, the *setting* dimension was used to distinguish between studies that were conducted in clinical and non-clinical settings. Additionally, we noted *data collection method(s)*, *participants* (physicians, nurses, patients or other) and *funding sources* for the studies. A summary description of each of the dimensions is provided in Table 1. The framework reflects the nature of research and the epistemological foundations of CI research in the considered time period.