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Methodological Review

Cognitive and learning sciences in biomedical and health instructional design: A review with lessons for biomedical informatics education

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ABSTRACT

Theoretical and methodological advances in the cognitive and learning sciences can greatly inform curriculum and instruction in biomedicine and also educational programs in biomedical informatics. It does so by addressing issues such as the processes related to comprehension of medical information, clinical problem-solving and decision-making, and the role of technology. This paper reviews these theories and methods from the cognitive and learning sciences and their role in addressing current and future needs in designing curricula, largely using illustrative examples drawn from medical education. The lessons of this past work are also applicable, however, to biomedical and health professional curricula in general, and to biomedical informatics training, in particular. We summarize empirical studies conducted over two decades on the role of memory, knowledge organization and reasoning as well as studies of problem-solving and decision-making in medical areas that inform curricular design. The results of this research contribute to the design of more informed curricula based on empirical findings about how people learn and think, and more specifically, how expertise is developed. Similarly, the study of practice can also help to shape theories of human performance, technology-based learning, and scientific and professional collaboration that extend beyond the domain of medicine. Just as biomedical science has revolutionized health care practice, research in the cognitive and learning sciences provides a scientific foundation for education in biomedicine, the health professions, and biomedical informatics.

1. Introduction

We approach the field of education and training in biomedicine and informatics as researchers in the area of cognitive and learning sciences. Biomedical informatics is becoming a part of biomedical curricula and, over time, it is likely to become a more integrated part of health professional and biomedical education. In this paper, we review the role of cognitive and learning sciences in addressing current and future needs in designing biomedical curricula, including biomedical informatics. In our view, the cognitive and learning sciences are an integral component of the basic science dimension of biomedical informatics education, and lessons from such work can inform practical issues in the design and implementation of training programs.

We begin this review by describing various theories of cognitive learning and their implications for instructional design and learning in general, and in biomedical curricula in particular. Essential to understanding how such theories provide a rationale for instructional design and learning is the nature and development of expertise and adaptive expertise [1], which is the subject of the next section of the paper. Investigators in this area, including authors of this review, have studied the acquisition of skilled performance and the organization of knowledge using a range of methods, including experimental, quasi-experimental, and naturalistic methods, which are described in Section 3.3. Subsequently, we provide a brief history of medical education and describe important types of medical curricula and current trends in this area (e.g., use of technology-based learning, incorporation of ethics and behavioral sciences into biomedical curricula), as well as an overview of empirical findings on research in this area. Although this section focuses on medical education, the lessons learned are equally applicable to other biomedical sciences such as training and education in biomedical curricula and informatics. The last section of this paper describes the role that technology plays in

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learning and instruction and the scientific basis that supports its use, as well as the impact of technology-based instruction on thinking and reasoning. This review concludes with a summary of how reform in biomedical curricula, including changes in instructional design and the education process, can find its scientific base in cognitive and learning sciences, emphasizing lessons for biomedical informatics. It should be noted that the review presented in this paper does not provide a comprehensive account of all learning theories and research on expertise and curricula in medicine; we have restricted our discussion to more current and influential cognitive learning theories, excluding behaviorist and other learning theories and instead emphasizing medical expertise and curricular research that is conducted using a cognitive framework, including our own contributions in this area. The reason for excluding behaviorist theories is that these have been devoted almost exclusively to simple learning, relating environmental conditions to overt behavior, eschewing the underlying brain or cognitive processes, and have therefore found little applicability to the kind of complex learning that goes on in knowledge-rich domains, such as biomedicine.

Medicine is a complex, multifaceted, knowledge-rich domain encompassing a range of performance skills and knowledge domains. Clearly, it is not likely that any one pedagogical or learning theory will adequately account for all skills and knowledge involved in biomedical instruction. However, research on medical expertise is beginning to inform the development of medical competence in real-world settings. Although this research may be used to suggest changes to the structure of medical and biomedical informatics education, we still need to understand more about the conditions of learning that lead to optimal levels of performance. In addition, much of the practice of medicine is collaborative in nature, and cognition in the workplace is shaped by the social context as well as the technological and other artifacts that are embedded in the physical setting. In medicine, the attainment of expert-level performance in the workplace is predicated on the subject's ability to function smoothly in an environment in which the coordination of tasks, decisions, and information is essential [2]. In complex dynamic decision-making environments, the situational and distributed aspects of expertise are emphasized—such as communication capabilities, the ability to convey plans and intentions, and the allocation of resources not only for one's self, but for others. Learning in such circumstances necessitates the development of pattern recognition capabilities that lead to rapid, heuristically-guided decisions under conditions of uncertainty and incomplete information. It also necessitates a complex socio-cognitive coordination process in which information-gathering, decision-making and patient management are highly interactive and distributed activities [3].

1.1. Cognitive science as key content in biomedical informatics education

We believe that the cognitive and learning sciences—the multidisciplinary field involving cognitive psychology, cognitive anthropology, linguistics, philosophy and artificial intelligence—have a foundational role in biomedical informatics education and training [4,5]. Cognitive science in particular has had a close relation to the biomedical field. Medicine has been a test-bed for cognitive science theories, and historically, was one of its first areas of application [6]. Research in cognitive science in medicine has also contributed to the conceptual and empirical development of the cognitive sciences (e.g., the study of diagnostic reasoning). Furthermore, a. number of areas central to biomedical informatics, such as the usability of information technologies; the processes of technology-supported decision-making and problem-solving; the comprehension of information to deliver Internet-based health care; and the design and implementation of collaborative tools in our increasingly interconnected health care environment, can benefit greatly from an understanding of the fundamental principles underlying human learning and performance [5]. Table 1 presents an illustration of how some biomedical informatics issues parallel those in the cognitive and learning sciences.

In addition, there are further motivations for including the cognitive and learning sciences as a foundation for biomedical informatics training. First, human and organizational issues in biomedical informatics are involved in many of the grand challenges that our discipline faces and that must successfully overcome [7,8]. Second, the cognitive and learning sciences are critical in providing a theoretically-based account of numerous issues underlying those challenges. Third, because the cognitive and learning sciences look at fundamental psychological and social processes, they allow us to have an in-depth understanding of the mechanisms of many practices essential to our discipline. In particular, understanding the issues involved in learning biomedical informatics concepts and skills seem essential for effective education and practice. It is accordingly important for biomedical informaticians to understand the concepts that have been developed in the major theories of learning.

2. Overview of learning theories

Although learning most often occurs informally through everyday experiences, and competence can be achieved without formal training, the rapid advances and the accumulation of knowledge in the sciences makes it unlikely that someone could attain proficiency and especially achieve full mastery of a domain without undergoing formal training.

Table 1
Examples of areas of mapping between cognitive and learning sciences and biomedical informatics.

Cognitive & learning sciences	Medical cognition	Biomedical informatics
Memory	Clinical case recall	Decision aids and reminders
Knowledge organization	Medical schemata & scripts	Knowledge and data representation
Problem-solving	Diagnostic and management clinical problem-solving	Medical information management
Heuristics and strategies	Reasoning strategies in diagnostic and patient management	Computer-based reasoning methods
Decision-making	Medical decision-making	Cognitive assessment of human-computer interaction in decision support system design, implementation, and use
Collaborative learning	Student and resident learning in medical teams	Targeted training in tele-medical applications
Anchored instruction	Learning in the ICU and other hospital environments	Usability of medical instrumentation to optimize learning
Apprenticeship	Cognitive learning of patient management at the bedside	Design and assessment of tutoring systems in medical informatics training
Discourse analysis	Medical discourse	Medical coding systems and ontologies