DOI: 10.15386/cjmed-530

THE DEVELOPMENT OF SCIENTIFIC REASONING IN MEDICAL EDUCATION: A PSYCHOLOGICAL PERSPECTIVE

DANIELA LUMINITA BARZ, ANDREI ACHIMAŞ-CADARIU

Department of Medical Education, Iuliu Hatieganu University of Medicine and Pharmacy, Cluj-Napoca, Romania

Abstract

Scientific reasoning has been studied from a variety of theoretical perspectives, which have tried to identify the underlying mechanisms responsible for the development of this particular cognitive process. Scientific reasoning has been defined as a problem-solving process that involves critical thinking in relation to content, procedural, and epistemic knowledge. The development of scientific reasoning in medical education was influenced by current paradigmatic trends, it could be traced along educational curriculum and followed cognitive processes.

The purpose of the present review is to discuss the role of scientific reasoning in medical education and outline educational methods for its development.

Current evidence suggests that medical education should foster a new ways of development of scientific reasoning, which include exploration of the complexity of scientific inquiry, and also take into consideration the heterogeneity of clinical cases found in practice.

Keywords: scientific reasoning, medical education, evidence-based medicine, clinical reasoning

Introduction

Scientific reasoning has been studied from a variety of theoretical perspectives, which have tried to identify the underlying mechanisms that are responsible for the development of this particular cognitive process. Scientific reasoning has been defined as a problem-solving process that involves critical thinking in relation to content, procedural, and epistemic knowledge [1,2].

One specific approach to the study of scientific reasoning has focused on the development of this cognitive skill throughout medical education. Scientific reasoning has become an essential skill to develop throughout medical education due to the recent emphasis on evidence-based medicine (EBM). The patient-centered approach to clinical practice and the "best evidence paradigm" have had an impact on academic content, teaching methods and curricular structure of the medical education. Several studies into medical pedagogy have discussed the major types of medical curricula in relation to their capacity for nurturing essential skills for clinical expertise [3].

In order to provide an up-to-date review on the role of scientific reasoning in medical education, we comprehensively searched PubMed, ScienceDirect and APA electronic databases for relevant articles, without publication year restrictions. A combination of search terms such as scientific reasoning, medical education, evidence-based medicine, clinical reasoning revealed 87 articles. With appropriate selection based on relevancy and overall impact, 25 articles were considered.

The aim of this review is to discuss evidence that reveales the role of scientific reasoning in medical education and outline educational methods for its development development.

Scientific reasoning

Scientific reasoning has been studied across several distinct domains – cognitive sciences, education, developmental psychology, even artificial intelligence –

Manuscript received: 05.08.2015
Accepted: 01.09.2015
Address for correspondence: luminita.barz@umfcluj.ro

which have tried to identify its underlying mechanisms. Although research has defined scientific reasoning through different rationales, a common approach refers to the mental processes used when reasoning about scientific facts or when engaged in scientific research. There is no doubt with regard to the involvement of several general cognitive processes in the emergence and development of scientific reasoning, such as inductive reasoning, deductive reasoning, problem-solving and causal reasoning [4].

Although mental processes involved in science have intrigued researchers since the 1620, it was not until Simon and Newell (1971) that an actual theory of scientific reasoning was proposed. Simon and Newell defined scientific reasoning as a problem-solving process, which included a *problem space* consisting of the initial state, the goal state, and all the possible states in between, and *operators,* which were the actions that can be taken in order to move from one state to the other. According to the *problem space theory*, by investigating the types of representations people had and the actions that they took to get from one state to another, one could understand scientific reasoning [1].

Over time, a contrasting approach emerged which focused on studying the concepts that people hold about scientific phenomena. This approach brought forth the argument referring to the aspect of knowledge-dependency of reasoning. According to the *domain-specific* approach, a scientific reasoning task required participants to use their conceptual knowledge of a particular scientific phenomenon. In opposition, the *domain-general reasoning* approach focused on problem-solving strategies and cognitive processes that transcended specific domains and were applied in scientific discovery, the development of theories, experimentation and evidence evaluation [5]. Therefore, these two distinct approaches emphasized either conceptual knowledge or experimentation strategies.

Klahr and Dunbar's Model of Scientific Discovery (1988, *SDDS – Scientific Discovery as Dual Search*) has been the most preeminent attempt to integrate both knowledge acquisition, as well as cognitive mechanisms in order to provide a framework for the development of scientific reasoning [6]. The SDDS Model, influenced by Simon and Newell's theory of problem-solving, described scientific reasoning as a guided search within two related problem spaces – the *hypothesis space* and the *experiment space.* Klahr and Dunbar found that this search was bidirectional, one could move from the hypothesis space to the experiment space or vice versa, the primary goal being the discovery of either a hypothesis or a theory.

This conceptualization has recently been complemented by the *scientific argumentation* approach. This recent approach has focused on science pedagogy and it postulated the use of scientific discourse as "the new focus for scientific reasoning activity" [2]. By shifting the focus from the classical scientific experimentation approach to the socially-constructed scientific knowledge approach, scientific reasoning has broadened its conceptual framework. This view on scientific reasoning has emphasized the importance of *evidence evaluation* and coordination, for the advancement of scientific knowledge.

The current trend moved toward a unified approach for the study of scientific reasoning, which brought together both the psychological and the philosophical perspective. According to the philosophical perspective, scientific reasoning was essentially critical thinking in relation to *content, procedural, and epistemic knowledge* [2]. The unified approach proposed by Kind referred to a combination of Giere et al's work with the SDDS model through which we could explain how "expert scientists are better at scientific reasoning because they have superior understanding of these three knowledge types". Therefore, scientific reasoning refers to both the cognitive process, which, based on Kind's approach, involved hypothesizing, experimenting, and evidence evaluation, as well as content, procedural, and epistemic knowledge.

Educational perspectives on the development of scientific reasoning

Developing scientific reasoning across education has raised many viewpoints with regard to early developmental processes, specific teaching methods in science education, evaluation of scientific literacy and so on. In this section, we will only be revising the most relevant educational theories with regard to the development of scientific reasoning in medical education, with special attention given to cognitive learning approaches.

The first major educational approach has focused on the interaction between different aspects of scientific thinking in a collaborative setting, rather than analyzing "the product of one person thinking alone" [4]. This view regarding the development of scientific reasoning was specific to the constructivist theory of education, according to which learning was an active process rather than an independent mechanism of knowledge acquisition. According to the constructivist learning theory, developing scientific research skills in students involved, primarily, changing their beliefs in line with the scientific principles shouldered by the community. Constructivism provided the philosophical bases for the conceptual change toward "building skills", perceived also in medical education [7,8].

The second educational approach has placed authentic learning environments as the foundation for developing reasoning skills in students. The "Situated learning theory" or "Situative learning theory" [9] offered an instructional approach according to which students were more inclined to learn by actively participating in the learning experience. This perspective claimed that procedural knowledge acquisition took place through problem-solving; the novice was immersed in a context that involved other people who were experienced at solving similar problems [3].

One other main theoretical direction, which attempted to provide foundation for the development of scientific reasoning throughout education, related to the cognitive perspective. The Adaptive Character of Thought (ACT-R) theory, developed by Anderson [10], proposed that cognition arose from the interaction of procedural and declarative knowledge. Procedural knowledge consisted of *production rules*, which represented the "how to", while declarative knowledge consists of facts, organized in units called *chunks*, which represented the "what". The individual units were created by encodings of objects in chunks or encoding of transformations in production rules. According to the ACT-R theory, "human cognition depends on the amount of knowledge encoded and the effective deployment of the encoded knowledge" [10,11].

As an attempt to integrate the role of memory into educational theory and practice, Sweller and Chandler [12] proposed the *Cognitive Load Theory* (CLT). CLT suggested that effective instructional resources would facilitate learning through relevant directed activities and an ineffective instructional design required learners to integrate disparate, split-source information, which might generate heavy cognitive load. Based on Sweller and Chandler's research findings, in areas where complex knowledge acquisition was necessary in order to assimilate more than two sources of information, conventional teaching should be replaced by integrated instructional designs.

To summarize, the development of scientific reasoning in medical education could be traced along these two major influences: *cognitive learning theories*, which focused on individual cognitive processes, and *constructivist learning theories*, which focused on interaction within an educational setting; both perspectives provided valuable support for the design and implementation of educational methods applied in medicine [9].

Based on these findings, medical curriculum has integrated academic content, teaching methods and curricular structure to adapt to the students' needs. Research into medical pedagogy has revealed two major types of medical curricula: the conventional approach and the problem-based learning approach (PBL) [9].

The conventional approach referred to the classical division of stages: preclinical (1st and 2nd year) and clinical (from the 3rd year to final year). The division was based on the difference between educational objectives between fundamental sciences, which provided basic scientific knowledge, and clinical sciences, which provided clinical knowledge. According to the conventional curricular approach to medical education in Romanian universities, a model for the development of scientific reasoning is presented in Figure 1.

Problem-based learning curriculum focused on a blended approach to knowledge acquisition, which combined scientific content with practical problem-solving tasks. Teaching methods aimed at facilitating self-directed and collaborative learning, while developing critical thinking skills. PBL has emerged as a solution for the ineffectiveness of scientific content taught abstractly for skills development in clinical practice [9]. However, research findings have not been conclusive regarding the differences in clinical skills or even critical thinking, between students from conventional and PBL programs. Pardamean [13] has investigated change in critical thinking skills of dental students educated in a PBL curriculum, using the Health Sciences Reasoning Test (HSRT – psychometric measure for critical thinking, analysis, inference, evaluation, deductive reasoning, and inductive reasoning). Results showed no significant differences in critical thinking scores throughout education on a PBL curriculum. While results were contradictory, some researchers strongly believed in a medical curriculum based on problem solving principles of applying new knowledge in practical tasks and "promoting learner responsibility" [7].

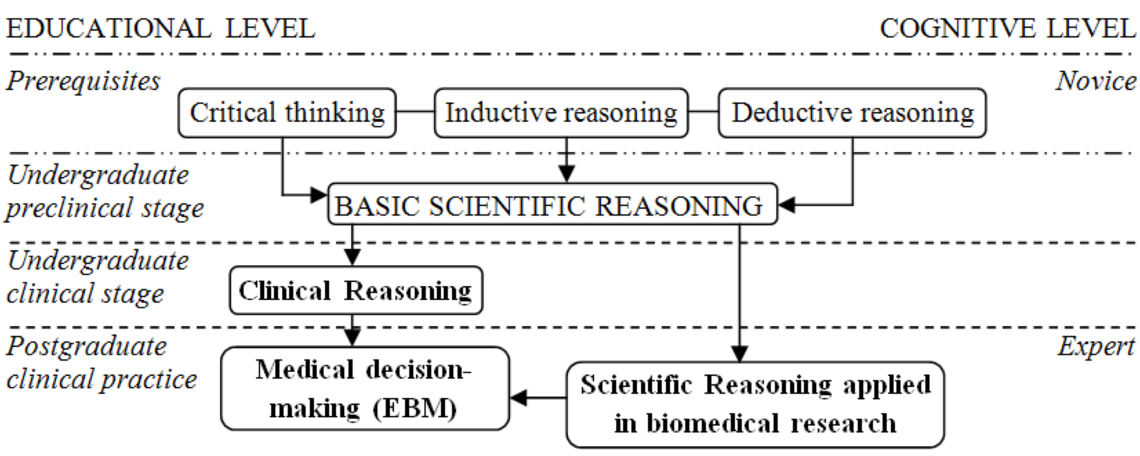

Figure 1. Conventional model for the development of scientific reasoning in medical education.

Scientific reasoning and clinical expertise

Studies on clinical expertise revealed contradictory findings regarding domain-specific versus domain-general competency and it was perceived in relation to current paradigmatic trends. Evidence-based medicine has been defined as “the conscientious, explicit, and judicious use of the best evidence in making decisions about the care of individual patients” [14]. Although EBM has been around for centuries, the focus on using the best evidence in medical research to treat patients began in the late 1980s in Canada and the United Kingdom [15]. It has been termed as a *paradigm shift*, however debates were continuing over the philosophical underpinnings and the practical nature of EBM. Sehon and Stanley [16] strenuously challenged the notion of ‘paradigm shift’, arguing that definitions of EBM were vacuous because they merely emphasized the use of the best evidence available, “as if any alternative to EBM means doing medicine based on something other than evidence”. In turn, Sehon and Stanley suggested that advocates of EBM should have emphasized the essence of what separated EBM from the other approaches, which was the priority it gave to certain forms of evidence, such as randomized clinical trials (RCTs), systematic reviews and meta-analyses of RCTs.

Apart from the limitations discussed by Sehon and Stanley, EBM has ignited reluctance due to its mechanical and reductionist approach to medical practice. Miles and Loughlin discussed the potential harmful effects of EBM and the possible new benefits found with Person-Centred Medicine (PCM) [17]. They referred to Tournier, a medical practitioner, who firstly mentioned the dangers of depersonalized clinical practice, “lacking the integration of body, mind and spirit necessary for health and wholeness and overlooking the healing potential of the therapeutic relationship”. They also argue that, from a person-centred perspective, EBM fails to incorporate patients’ “values and preferences into clinical decision making, when these are in conflict with EBM’s ‘evidence’ ”. Thus, the methodological challenge would be to integrate biomedical findings and technological advances “within a humanistic framework”, without undermining applied science into medical education.

Studies on clinical expertise revealed that differences between experts and novices were more complex when it came to biomedical knowledge. Several studies on medical students’ research skills aimed at exploring scientific reasoning and critical thinking skills [18,19,20]. Msaouel et al. [19] aimed at researching familiarity of medical residents with statistical concepts, evaluated their ability to integrate these concepts in clinical scenarios and investigated cognitive biases in particular judgment tasks. They used a multi-institutional, cross-sectional survey, which focused on basic statistical concepts, biostatistics in clinical settings and cognitive biases. Results showed that out of 153 respondents, only 2 were able to answer all biostatistics knowledge questions correctly, while 29 residents gave incorrect answers to all questions (the majority were susceptible to cognitive bias tasks).

Schunn and Anderson [21] performed a study on the domain-general or domain-specific nature of scientific reasoning skills. They used *think aloud protocols* to investigate differences in designing experiments between domain experts, experts skilled in other domains and undergraduate students. Results showed that domain experts and “other experts” differed in terms of domain-specific skills, while “other experts” and undergraduate students differed with respect to domain-general skills. By analyzing verbal protocols, Schunn and Anderson were able to identify domain-general skills that seem more important in scientific reasoning than domain-specific skills.

Another such study used memory probes to identify possible differences between students, residents and internists, in diagnostic competency. Participants were asked to read case histories, assign diagnoses before tasks of free recall, cued recall, and recognition tests. Students’ performance was superior to that of internists, while residents’ performance was more variable [22]. These results suggested that students focused more on the details of a clinical case, their procedural knowledge was closely tied to the amount of information they possessed, while clinicians took on a larger perspective when assessing diagnosis. This idea has been explored in-depth by Schmidt and Boshuizen [23,24] who have proposed the concept of “knowledge encapsulation”. “Knowledge encapsulation is the subsumption, or “packaging,” of lower level detailed propositions, concepts, and their interrelations in an associative net under a smaller number of higher level propositions with the same explanatory power.” According to this theory, novices processed, in a bottom-up manner, detailed knowledge with regard to a clinical case, leading to increases in free-recall, “as a function of the growth of the knowledge base”. Experts, being exposed to more and more similar clinical cases, used certain shortcuts in their diagnoses, facilitated by “encapsulated knowledge”. However, Schmidt et al. have suggested that clinical expertise is a process of reaching three kinds of mental representations: basic mechanisms of disease, illness scripts, and exemplars derived from prior experience [24].

In his chronological review of research into clinical reasoning, Norman concludes that there is no clinical reasoning as a stand-alone concept, but rather experts used multiple knowledge representation and the cognitive flexibility and skill adaptation allowed the expert to perform successfully [25]. Four levels of expertise in medical education have been proposed [9]: (1) novice (possesses the prerequisites or basic knowledge required, like the 1st year student); (2) intermediate (possesses above the beginner level but below the sub-expert level, like the 2nd year student; (3) sub-expert (possesses general knowledge but insufficient specialized domain knowledge, like a resident; and (4) expert (possesses sufficient specialized domain knowledge, like a consultant physician). According to Norman's review, any type of expertise should be viewed as a developmental path from novice to expert, which can be facilitated through efficient instructional designs, but which also has many intermediate phases.

Conclusions and future directions

From a psychological perspective, educational theories can provide the foundation for teaching methods and curricular improvements, in terms of advancing scientific reasoning throughout medical education. Constructivism provides the philosophical bases for the conceptual change needed in science education, present in medical education as well. Clinical reasoning, diagnostic reasoning, and clinical decision-making are terms that have been used in a growing body of literature that examines how clinicians assign diagnoses and make medical decisions. However, clinical reasoning is being shaped starting with undergraduate medical education. Medical educators' definitions of superior clinical reasoning will invariably influence their choices in shaping the thought processes of future doctors. In addition, principles of ACT-R can provide medical education with support through cognitive tutors, which are computer-based instructional systems that simulate student behavior. Implementation of a cognitive tutors program within clinical practice would provide medical students with essential knowledge-based support for efficient learning and skills training [6,9,11]. On the other hand, medical education involves acquisition of a large amount of both procedural and declarative knowledge. Instructional designs within medical education should also take into consideration research findings regarding the role of memory and cognitive processes in relation to short-term and long-term acquisition [12].

From a medical standpoint, medical education and clinical practice are influenced by two contrasting approaches: EBM and PCM or PM (Personalized Medicine). Theorists and practitioners both have discussed issues which arise from this segregation. First of all, the most important issue is to develop scientific methodologies which would integrate both EBM and PM, that would involve personalizing clinical and research guidelines, but also offering a rigorous framework for the person-centered approach. Secondly, medical education should foster a new way of scientific reasoning that includes exploration of the complexity of scientific inquiry, but also appreciation for the heterogeneity found in clinical practice. Clinical cases should be examined in problem-solving terms and placed under scrutiny through self-directed search and discovery. Trainees should be presented at all times with both possible outcomes – effect vs. no-effect; this way, both alternatives become legitimate conclusions to be reached and students can understand the more complex nature of scientific discovery. Future directions regarding the development of scientific reasoning in medical education should also focus on mapping clinical expertise. Although studies into expertise have encountered inherent limitations, building on a gradual developmental expertise acquisition and identifying novices' and experts' mental representations in clinical scenarios can provide valuable insight for future research.

Acknowledgements

This paper was published under the frame of European Social Fund, Human Resources Development Operational programme 2007-2013, project no POSDRU/159/1.5/138776.

References

1. Simon HA, Newell A. Human problem solving: The state of the theory in 1970. American Psychologist. 1971;26:145-159.
2. Kind PM. Establishing Assessment Scales Using a Novel Disciplinary Rationale for Scientific Reasoning. J Res Sci Teach. 2013; 50(5): 530–560.
3. Patel VL, Yoskowitz NA, Arocha JF, Shortliffe EH. Cognitive and learning sciences in biomedical and health instructional design: A review with lessons for biomedical informatics education. J Biomed Inform. 2009;42(1):176-197.
4. Dunbar K, Fugelsang J. Scientific Thinking and Reasoning. In Holyoak KJ, Morrison RG, The Cambridge Handbook of Thinking and Reasoning. Cambridge University Press; 2005:705,720.
5. Zimmerman C. The Development of Scientific Reasoning Skills. Developmental Review. 2000;20:99–149.
6. Klahr D, Dunbar K. Dual Space Search During Scientific Reasoning. Cognitiv Science. 1988;12:l-48.
7. Colburn A. Constructivism: Science Education's "Grand Unifying Theory". Clearing House. 2000;74(1):9-12.
8. Maudsley G, Strivens J. Promoting professional knowledge, experiential learning and critical thinking for medical students. Med Educ. 2000;34(7):535-544.
9. Lave J. Situating Learning in Communities of Practice. In Lave J, Wenger E, (pp.63-82) Situated Learning Legitimate Peripheral Participation. Cambridge University Press; 1991.
10. Anderson JR. ACT: A simple theory of complex cognition. American Psychologist. 1996;51:355-365.
11. Koedinger KR, Anderson JR. Illustrating principled design: The early evolution of a cognitive tutor for algebra symbolization. Interactive Learning Environments. 1998;5:161-180.
12. Chandler P, Sweller L. Cognitive Load Theory and the Format of Instruction, Cognition and Instruction. 1991;8(4):293-332.
13. Pardamean B. Measuring change in critical thinking skills of dental students educated in a PBL curriculum. J Dent Educ. 2012;76(4):443-453.
14. Sackett DL, Rosenberg WM, Gray JA, Haynes RB, Richardson WS. Evidence based medicine: what it is and what it isn't. BMJ. 1996;312:(7023):71-72.
15. Mayer D. Essential Evidence-Based Medicine. 2nd ed. Cambridge University Press; 2010:10-11.
16. Sehon SR, Stanley SE. A philosophical analysis of the evidence-based medicine debate. BMC Health Serv Res. 2003;3(1):14.
17. Miles A, Loughlin M. Models in the balance: evidence-based

medicine versus evidence-informed individualized care. J Eval Clin Pract. 2011;17(4):531-536
18. Green ML. Evidence-based medicine training in internal medicine residency programs a national survey. J Gen Intern Med. 2000;15(2): 129–133.
19. Msaouel P, Kappos T, Tasoulis A, Apostolopoulos AP, Lekkas I, Tripodaki ES, et al. Assessment of cognitive biases and biostatistics knowledge of medical residents: a multicenter, cross-sectional questionnaire study. Med Educ Online. 2014;19:23646.
20. Holloway R, Nesbit K, Bordley D, Noyes K. Teaching and evaluating first and second year medical students' practice of evidence-based medicine. Med Educ. 2004;38(8):868-878.
21. Schunn CD, Anderson JR. The Generality/Specificity of Expertise in Scientific Reasoning. Cognitive Science. 1999;23(3):337-370.
22. Eva KW, Norman GR, Neville AJ, Wood TJ, Brooks LR. Expert-novice differences in memory: a reformulation. Teach Learn Med. 2002;14(4):257-263.
23. Schmidt HG, Boshuizen HPA. On the origin of intermediate effects in clinical case recall. Mem Cognit. 1993;21(3):338-351.
24. Schmidt HG, Norman GR, Boshuizen HPA. A cognitive perspective on medical expertise: theory and implication. Acad Med. 1990;65(10):611-621.
25. Norman G. Research in clinical reasoning: past history and current trends. Med Educ. 2005;39(4):418-427.