Critical Issues in Dental Education

Knowledge Integration and Reasoning as a Function of Instruction in a Hybrid Medical Curriculum

Vimla L. Patel, Ph.D., D.Sc.; Jose F. Arocha, Ph.D.; Sumedha Chaudhari, M.Sc.; Daniel R. Karlin, M.A.; Dalius J. Briedis, M.D.

Abstract: This study investigates the effect of curricular change on knowledge integration and reasoning processes during problem-solving by medical students. The curricular change involved the introduction of problem-based, small group tutorials into a conventional health science curriculum (CC). Students at three levels of training were asked to provide diagnostic explanations of two clinical cases, both before (spontaneous) and after (primed) being exposed to basic science information relevant to the clinical problems. Data were analyzed using techniques of propositional and semantic analysis. Based on theories of instruction and cognition, we expected that the instructional changes would facilitate knowledge integration and influence the reasoning patterns of the students. The results show that students generated fewer inferences and used more information from the basic science text (text-based) to explain the clinical problems. However, they generated a greater number of elaborations during explanations using a mixture of data-driven and hypothesis-driven strategies. The spontaneous and primed problem-solving conditions produced more hypothesis-driven and data-driven strategies, respectively, as would be expected in a hybrid curriculum. We conclude that a) problem-based, small group tutorials facilitate integration of clinical and biomedical knowledge through the use of elaborations and hypothesis-driven strategies, and b) aspects of problem-based learning can be successfully integrated into traditional curricula.

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Problem-based learning (PBL) curricula have been implemented in many health sciences schools in North America and other parts of the world. PBL attempts to meet three objectives: organize biomedical and clinical knowledge around a patient problem, develop the clinical reasoning process, and enable self-directed learning. PBL is characterized by its integration of all basic science into a clinical problem context. Basic science knowledge is taught in this way for two reasons: first, to make knowledge more relevant and retrievable; and second, to foster the development of specific reasoning strategies. The typical learning format for PBL curricula are small group tutorials of five or six students with a trained faculty tutor. Students work collaboratively and, in an important sense, take responsibility for their own learning. Over the past several years, components of PBL have been increasingly included in dental education programs. The addition of PBL components to dental education, the continual refinement of these components, and the effects of the curricular changes on dental education as a whole have been addressed in the literature.

Several studies of PBL have found small group tutorials to be an effective learning method and have been favored over the lecture format by students. Students have reported positive effects of PBL in terms of use of additional learning resources, in-
crease level of independence, positive attitude, and teamwork and motivated learning. PBL has consistently produced enhanced work environments for students and faculty and has been found to be a means by which collaboration between institutions may be improved.

In contrast to PBL, the conventional curriculum (CC) is characterized by the lecture format. Basic science knowledge is taught in the first years of schooling before clinical information is applied. Studies have shown that CC students feel more confident in their knowledge base when solving clinical problems and seem to possess better communication skills. Furthermore, in contrast to PBL students, CC students tend to use mainly data-driven reasoning, i.e., from the given information to the hypothesis. Data-driven reasoning, also known as forward reasoning, has been shown to be a hallmark of expert problem-solving in routine situations in many domains, including medicine. It appears that CC students learn to reason in an expert-like manner by their early exposure to clinical mentorship in their training.

Research has uncovered other differences between CC-trained and PBL-trained students. In national examinations in the United States and Canada, PBL students score better on clinical information sections than their CC counterparts, but less well on tests of basic science knowledge. However, one study of the national means in the United States found the opposite effect. Research on the psychological basis of PBL shows that over several years PBL may increase the retention of knowledge and also appears to contribute to the development of professional competencies. However, a recent review of literature from 1992 through 1998 on the credibility of claims about the ties between PBL and education outcomes revealed no convincing evidence that PBL improves the knowledge base and clinical performance of health sciences trainees. Further, Colliver concluded that although PBL might provide a more challenging, motivating, and enjoyable approach to health sciences education, its educational effectiveness remains to be seen when compared with more conventional formats.

Other studies have compared perceptions of health sciences education among students and graduates from three Dutch medical schools, one of which was a PBL school and the others conventional. Participants completed self-assessments of their psychological, interpersonal, and clinical patient management skills. Those from the PBL program reported higher satisfaction with their training and better preparation in psychological and interpersonal skills. However, there was no difference, compared to those from conventional schools, in their reported ability to manage clinical situations. A survey study conducted by Shin et al. reported that graduates from a PBL school were more up-to-date regarding current clinical practice guidelines for hypertension than CC school graduates. They attributed this to the emphasis in PBL on promoting a more independent learning style.

A major difficulty with the standard ways of investigating performance in different curricula (i.e., comparing overall curricular effects) is that a curriculum is composed of a very complex collection of activities, involving many different components (e.g., small group teaching vs. lectures; expert vs. non-expert tutors) and many variations among these components (e.g., not all lectures are equivalent; tutors are often defined differently in different schools). The apparent success or failure of a particular curriculum format may be due to one or a combination of these components, rather than the curriculum as a whole. Under these circumstances, it is extremely difficult to determine which parts of the curriculum are responsible for the results and which are not. Rather than investigating overall differences between curricula, one may design experimental studies that look at behavior and cognition in controlled environments with an aim of teasing out causal factors; or one may focus on separate aspects of performance and examine these in detail, with the aim of providing detailed characterization of cognitive processes under specific real world conditions. In this and previous studies, we have taken this second strategy that illustrates cognitive performance under different conditions and describes the reasoning and knowledge integration processes of health sciences students or practitioners who have been trained in one type of curriculum or the other. Based on the differences in performance, we can then hypothesize the origins of differences in reasoning and problem-solving, based on established cognitive research and what we know about the respective curricula. This type of study, in turn, may suggest hypotheses for further investigation under controlled conditions or in large-scale quasi-experimental settings.

The study reported in this paper was conducted at McGill University in Montreal, Quebec, Canada. Since 1994, McGill’s medical school has used a new medical curriculum that integrates components of problem-based and conventional learning into a hybrid curriculum. The original goal of the new hybrid
curriculum was to create a program in which both horizontal integration of basic sciences across disciplines and vertical integration of biomedical and clinical knowledge would be optimized. In our study, we investigated two curricular aspects: 1) the extent to which students integrate basic science into clinical problems and 2) the types of reasoning strategies used in clinical problem-solving. The findings of this study are generalizable to any health sciences curriculum in which students integrate basic science and clinical information.

Knowledge Integration and Reasoning in the Health Sciences Curriculum

An assumption in health sciences education is that clinical medicine and the biomedical sciences form a unified domain where clinical symptoms can be causally attributed to their underlying pathophysiological mechanisms. Another assumption is that effective diagnostic reasoning involves the ability to explain the diagnosis in terms of such malfunctioning mechanisms, where one hypothesizes such mechanisms and deduces the observable consequences from them. These assumptions underlie the reasoning strategy known in the literature as the hypothetico-deductive method. The use of this hypothetico-deductive method is characteristic of the PBL curriculum, where it has been widely adopted. Indeed, its extensive use indicates that there may be something effective about it. However, the far-reaching nature of certain claims regarding its use, especially the idea that it can replace systematic teaching in the basic medical sciences, makes it important to be clear regarding what is being learned and how important are the diverse aspects of knowledge for fostering competent performance.

Previous research comparing knowledge structures and reasoning strategies of students from conventional and problem-based medical schools looked at the use of basic science knowledge and clinical knowledge in the explanations of clinical cases by medical students. In this research, students were given clinical problems to diagnose and explain, before or after they read basic science texts with relevant information about the clinical cases. The results showed that when basic science information was read before the clinical problem, students at both schools failed to integrate the basic science information into the clinical context. This lack of integration resulted in 1) a lack of global coherence in their explanations (i.e., their explanations consisted of isolated “chunks” of information with no explicit relationship among the chunks), 2) the presence of errors of factual information in such explanations, and 3) the disruption of the process of diagnostic reasoning. When the clinical problem was given alone, students from the conventional school used mostly clinical information and very little biomedical information. This pattern was more apparent with the increase in years of training. In contrast, students, including the beginning students, in the PBL school used detailed biomedical information. When basic science was given after the clinical problem, both conventional and PBL students showed integration of basic science into the clinical context, but PBL students demonstrated better integration than students from the conventional school. It was concluded that clinical problems cannot easily be embedded into a basic science context, but basic science can be embedded within the clinical context. Thus, the results by Patel et al. show that, in the conventional curriculum, 1) basic science and clinical knowledge are generally kept separate, 2) routine clinical reasoning does not require basic science knowledge (except for beginning students), 3) basic science is spontaneously used only when students get into difficulty with the patient problem, and 4) basic science serves to generate a globally coherent explanation of the patient problem with connections between various components of the clinical problem. In the conventional curriculum, the clinical aspect of the problem is viewed as separate from the biomedical science aspect, with the two aspects having different functions.

In contrast, in the PBL curriculum this integration was so tight that the students appeared to have problems in transferring what they had learned in one situation to another one (e.g., from one clinical problem to another). Furthermore, PBL students generated a greater number of elaborations resulting in the fragmentation of knowledge, where the various components of their explanations remained isolated (i.e., not connected). These elaborations resulted in factual errors all through the medical curriculum (from second- to fourth-year medical studies). The differences between the CC and PBL students could be due to the emphasis put by PBL on the detailed causal reasoning and elaboration, since this might be assumed to generate more load on working memory. However, these differences may be a short-
term effect of the undergraduate medical curricula, the long-term effect of which is not yet known.

In a subsequent article, Patel et al.\(^{28}\) investigated whether residents who had been trained in either CC or PBL showed the same pattern of reasoning and problem-solving found in medical students in their respective curricula. The results are telling: residents trained in the conventional curriculum focused on the given patient information, kept biomedical and clinical knowledge separate, and used predominantly data-driven strategies. In contrast, residents from the problem-based learning curriculum organized their knowledge around generated inferences, integrated biomedical and clinical knowledge, and reasoned using mostly hypothesis-driven strategies and a great deal of knowledge elaborations.

Although residents from both schools generated equal numbers of diagnostic hypotheses during the reasoning process, the residents from the conventional curriculum generated a greater number of accurate hypotheses than students in PBL, following the initial presentation of the patient history. The performance of the residents was basically identical to that shown by the medical students in their respective curricula. Despite the similarities in residence training between conventional and PBL residents, subjects from the PBL curriculum still reasoned predominantly in a hypothesis-driven fashion. Therefore, development of automated reasoning strategies such as data-driven reasoning, which is typical of expert physicians, appears to be impeded in the PBL curriculum. The conclusion we gathered from these results is that when one is learning two unknown domains, it is better to learn one well, in such a way that is used as an “anchor” for the new domain.

In this context, the alleged benefits of integrating basic science and applied clinical knowledge may not be achieved. Research by Pollock et al.\(^{31}\) lends support to this hypothesis. Pollock et al. investigated learning in two conditions. The first condition had all information integrated into a single explanation (high interactivity element material). This situation is similar to a situation in which biomedical and clinical information is learned in an integrated fashion. The second condition presented information in a piecemeal and sequential fashion; this situation resembled the conventional curricular teaching, where basic science is learned first and then used to gain clinical knowledge. Pollock et al. found that, at least for some of the subjects, the sequential process of learning led to better acquisition of knowledge than did the integrative process.

Another recent study\(^ {23}\) investigated the relationship between real-world PBL small group session and the corresponding large group lectures and found that, when in small group sessions, students base the discussion on information learned in the lecture setting, while expanding the topic to areas not directly covered in the lecture. In addition, while lectures focus on one specific area of discipline, the small group sessions allowed and encouraged students to integrate information from across a number of disciplines. Thus, small group sessions were found to demonstrate the relationship between broad lecture concepts and clinical problem-solving using numerous and diverse sources of information.

**Domain Anchoring and the Directionality of Reasoning**

As a consequence of knowledge integration and the explicit teaching of the hypothetico-deductive method, problem-based learning is assumed to foster the acquisition of hypothesis-driven reasoning patterns. Studies\(^ {28,32}\) have shown that students in PBL schools tend to use more hypothesis-driven reasoning (i.e., from the hypothesis to the given information) than do students in more conventional schools. In explaining clinical problems, PBL students produce extensive elaborations (e.g., detailed pathophysiological explanations) using relevant biomedical information, which contrasts with students trained in conventional curricula, who tend to use more data-driven strategies (from the data in the problem to a hypothesis). This finding has been attributed to PBL’s reorganizing students’ knowledge structures, in turn promoting the activation and elaboration of prior knowledge.\(^ {33}\)

Cognitive research in other domains has shown that specific training in hypothetico-deductive reasoning may have a detrimental effect on performance due to “schema disruption” and “knowledge fragmentation.” That is, students fail to learn the full representation of a problem or topic, learning in its place a collection of unrelated facts. The generation of schemas is required for successful problem solving, as it has been shown in previous research by a number of investigators.\(^ {13,34,35}\) Studies conducted by Chandler and Sweller\(^ {15,37}\) have shown that giving students problems to solve while training them in the use of problem-solving strategies at the same time results in a heavy cognitive load and weakens students’ abil-
ity to focus. Instead, they split their attention between learning the strategies and learning the content of the material. To learn a topic well, students must allocate their cognitive resources to understanding content, rather than to problem solving. As Chandler and Sweller explained, hypothesis-driven reasoning hinders the construction of problem schemata, resulting in the fragmentation of knowledge. Similar results were found by Vollmeyer et al., working in the domain of biology, who showed that hypothesis-driven reasoning failed to provide an effective method of inductive learning and may hinder the ability to transfer learning. However, results of a study by Norman et al. appear to challenge these results. A group of psychology students were encouraged to use data-driven reasoning by instructing them first to obtain the data, synthesize it, and then make the diagnosis, whereas a second group were asked first to hypothesize a diagnosis and later to find supporting data for the hypothesis. They found that subjects using hypothesis-driven reasoning were more accurate than those using data-driven reasoning. We believe that such differences can be explained in terms of the tasks the subjects were asked to perform. In the Chandler and Sweller and Vollmeyer et al. studies, subjects were trying to learn a topic while learning at the same time a method of approaching the problem, whereas there was no dual learning in the Norman et al. study. This dual learning and the resulting allocation of cognitive resources to both tasks may be responsible for poor performance. Because of this distinction, we do not think that the Norman et al. study challenges the finding that experts use data-driven reasoning or the deficiencies of “dual-learning,” but it suggests that, in certain situations, providing a hypothesis to naïve subjects may lead to better accuracy than leaving these subjects to their own devices.

Although the introduction of PBL components into the McGill curriculum (e.g., small group tutorials) was expected to benefit students by allowing them to learn better the underlying basic science knowledge and integrate it into clinical knowledge, it has been shown in cognitive science literature that a) when learning two unknown domains, it is better to learn one well, in such a way that it is used as an “anchor” for the new domain; b) basic science knowledge, which has a causal underlying structure that can be remembered as a story, can serve this anchoring role; c) clinical knowledge, which has a classificatory structure of signs, symptoms, and diseases, may be difficult to learn without the anchoring support of the underlying basic science knowledge; and d) the anchoring of one domain on the other may promote the use of data-driven reasoning by providing a foundation for clinical problem solving. The McGill curriculum provides this basic science anchor through the lecture series, as well as through assigned readings. The small group program is used to complement these lectures (e.g., by expanding and elaborating upon the lectures). One may argue that such a program will provide the students with all the benefits of PBL as discussed above. The benefit of the McGill curriculum is that while it makes use of a PBL-like approach, which increases clinical knowledge and student interest, it also makes use of a more conventional approach for the teaching of the basic sciences. Teaching basic sciences through a conventional approach has been shown to give the student a better understanding of the material.

**Methods**

**Subjects, Clinical Material, and Procedure**

Eighteen subjects were selected from three levels of medical school training at McGill University in Canada. Level 1 included six students in their second-year of medical school. These were the students who did not have much clinical exposure in the hospitals. Level 2 consisted of six third-year students in the middle of their medical training. Level 3 included six final-year students who had the most clinical exposure compared to the other subjects and were a few months from graduation. Individual tutorial groups of ten to fifteen students in their second, third, and fourth years of training were approached to take part in the study. Caution was taken to ensure that only those students who had never taken part in a similar experiment were included. The students were selected by a request for volunteers, with an offer of a token payment. In such a situation any volunteer bias would presumably favor more competent students.

Students at the McGill medical school are selected initially on the basis of their academic performance such as GPA and Medical College Admissions Test scores. There is a prerequisite of having scientific background in their undergraduate training. After this initial screening, students are selected by interview process, with letters of recommendation and an autobiographical letter emphasizing their personal
qualities. Approximately 20 percent of the students are selected from high school on the basis of merit. However, this was not the case in our study. From Table 1, which shows characteristics of the students who took part in this study, we can observe that the majority had at least the bachelor’s degree in science, a characteristic of the population at McGill medical school. The acronym “CEGEP” refers to “Collèges d’Enseignement Général et Professionnel,” a degree institution unique to Quebec, which provides two years of postsecondary education or three years of professional education. Two years of CEGEP education is the minimum level required to enter university for any resident of the province.

Two clinical texts and two basic science texts that provided information related to the two clinical cases were used as stimulus materials. The first clinical passage describes a forty-eight-year-old diabetic male who was originally admitted to hospital suffering from leg ulcers. The complete text of this clinical case is presented in the upper portion of Appendix 1. The patient was then given both intravenous and oral antibiotics to treat his condition. The antibiotics, however, were ineffective in controlling the infection. The patient later developed a resistant strain of the bacteria *Klebsiella oxytoca* in his wound. Although the patient was given an increased dose of the drug, his condition did not improve. The resistant organisms continued to divide and infect, first locally and then systemically. Finally, the patient became hemodynamically unstable and died due to cardiac arrest. As an illustration, in Figure 1 we present the reference model generated by an expert physician, showing the correct explanation of the problem.

The first basic science text passage is given in the lower portion of Appendix 1. This text presents information regarding the mechanism of antimicrobial drug resistance and the effect of hospital environments on the response of the patient’s immune system.

The second case describes a previously healthy seventeen-year-old male admitted to the hospital suffering from meningitis with septic shock. The patient had a prior two-day history of myalgias, arthralgias, and pharyngitis. At the time of admission he had low-grade fever and a purpurred rash. The patient was initially managed with intravenous fluids and broad spectrum of antibiotics (gentamicin, ceftriaxone, and vancomycin). Before finally recovering, however, he developed severe hypotension, oliguria, and severe respiratory failure for a short period of time, which were managed with appropriate care and medications. The results of various medical tests done before and during his hospital stay as well the medications given are also mentioned in the text. A reference model was generated by an expert physician, showing the correct explanation of the problem. The complete text of clinical case 2 that was provided to students is given in the upper portion of Appendix 2. The corresponding basic science text shown in the lower portion of Appendix 2 describes the role that lipopolysaccharide (LPS) and interleukin-10 (IL-10) play in patients with severe gram-negative shock.

Each subject was given a booklet with the description of Case 1 followed by the basic science text relevant to this case (Basic Science Text 1). The subjects were asked to read only the case (and not the following science text) and provide in writing the pathophysiology of the clinical case. This was the spontaneous explanation (i.e., explanation of case before reading the basic science text). Once they had completed their pathophysiological explanation of the clinical text, they were then asked to read the basic science text and provide the pathophysiological explanation a second time, taking into consideration the text they had just read. This is called the biomedically primed explanation. They were then asked to repeat the procedure for Case 2.

All subjects were tested individually. Before each session, the subjects were given an explanation of the task they had to perform, making sure they understood what was asked of them. They were also asked to provide some information about their academic background (e.g., schooling, area of study). The whole task took about forty-five minutes to complete.

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Table 1. Characteristics of the student cohort at McGill Medical School who took part in the study

<table>
<thead>
<tr>
<th>Student Characteristics</th>
<th>Percentage (N=18)</th>
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</thead>
<tbody>
<tr>
<td>Sex</td>
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<tr>
<td>Female</td>
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<tr>
<td>Male</td>
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<td>Science</td>
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<td>Nonscience</td>
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<td>Bachelor’s</td>
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</tr>
<tr>
<td>Master’s</td>
<td>12</td>
</tr>
<tr>
<td>Doctorate</td>
<td>5</td>
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</tbody>
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Figure 1. Reference model for clinical Case 1
Methods of Analysis

The techniques used in analyzing the data are given in various publications. Specifically, the techniques used in this study were propositional analysis and semantic network analysis, which are detailed in the methods section of an article published earlier in this journal and only summarized briefly here. The method starts by breaking down the response protocols and the stimulus text passages into clauses and then into propositions and, finally, examining relations between these propositions. Simply put, a proposition is comprised of two concepts and a relation between the concepts.

Propositional analysis can be used to compare the subjects’ protocols with the texts they have read. Scoring used involves marking as verbatim every proposition in one text that corresponds exactly to the message in the second text. To conduct the mapping between the text and the physician’s verbalization, each proposition in the verbalization is listed side by side with the corresponding proposition in the text.

Because a propositional representation consists of a list of coded propositions, it is difficult to visualize the whole structure of a text. A propositionally analyzed text may look like a list of unrelated propositions. A follow-up step in the analytical process involves performing a semantic network analysis, which provides a picture of the whole semantic representation at any desired level of detail. Conceptual or semantic networks are graphs involving a non-empty set of nodes and a set of links connecting such nodes. Nodes often represent objects, clinical findings, hypotheses, or steps in a procedure, whereas links represent directed connections between nodes. One can think of semantic networks as being complementary to propositional representations, making it possible to visualize the relational structure of the propositions in their totality. Within this structure, propositions that describe attribute information form the nodes of the network (the semantic structures), and those that describe relational information form the links (the logical structures).

In this manner, one can have a measure of the coherence of a piece of text, in which coherence is defined as the overall connectivity of the network. A network in which all concepts are related would be identified as maximally coherent; a network where none of the concepts are linked would be defined as totally incoherent. Most texts possess some degree of coherence between these two extremes. Measuring the degree of coherence can be used as an indication of the extent to which people possess cohesive knowledge structures or have gaps in knowledge.

One can also have a measure of knowledge integration, which occurs when concepts from different sources become embedded into a single conceptual structure, creating a coherent explanation with both basic science and clinical propositions. Both concepts—integration and coherence—are operationalized with the help of semantic network analysis, in which concepts derived from explanation protocols are represented as graphs. As the number of independent, unconnected graphs decreases, so does the coherence of the explanation. Also, a more coherent explanation accounts for more data than a less coherent explanation. More detailed descriptions of the methods can be found in previous research.

Subjects’ protocols were also scored for three types of propositions: clinical text propositions (those present in the clinical problem); basic science propositions (those present in the basic science text); and inferences (those not present in any of the texts). Depending on whether they were based on clinical knowledge or basic science knowledge, the inferences were further broken down into clinical inferences or basic science inferences, as presented in Figure 2.

Semantic networks were generated from the propositional representations. As explained previously, semantic networks provide graphical representations of conceptual relations among propositions. The links between any two propositions in the semantic network structure are labeled to represent the type of relations in the network. Links labeled CAU (causal) indicate a causal relationship between adjoining nodes. Links labeled COND (conditional) indicate a conditional or “if then” type of relationship. Other types of links are resulting relations (labeled RSLT); location (LOC); and proximity relations (PROX).

The directionality of such relations within the semantics networks is important since causal rules generally lead away from a diagnosis (pathophysiology causes a clinical symptom) while conditional rules lead toward a diagnosis (a clinical symptom suggests pathophysiology). A network in which all rules lead from observable facts through intervening explanations to a final diagnosis is hypothesized to be generated by a process of pure data-driven reasoning.
contrast, a network in which all rules lead in the reverse direction, from diagnosis to facts, is hypothesized to be generated by pure hypothesis-driven reasoning. However, many networks show a mixed pattern that is neither purely data-driven (a characteristic of expert reasoning) nor purely hypothesis-driven (a characteristic of the reasoning of nonexperts).

To determine the directionality of reasoning, each network generated by the students was compared against the reference network for the types of links (relations) between the nodes (concepts). Specifically, a match between the response protocol and the reference model for a causal link was scored as a hypothesis-driven link, and a match for a conditional link was scored as a data-driven link. A relation that was neither causal nor conditional was scored as an elaboration. Finally, the frequency of these relations was counted in each of the experimental conditions. The data amenable to statistical analysis were analyzed using multivariate and univariate analysis of variance.

Results

The results will be reported in four categories: spontaneous explanation, biomedically primed problem solving, student-generated diagnoses, and summary of the results.

Spontaneous Explanation

Use of Basic Science and Clinical Knowledge. The mean number of propositions used and inferred from the clinical texts of Case 1 and Case 2 (prior to reading the basic science text) are given in the upper portion of Table 2. Generally, students generated longer explanations for Case 1 than for Case 2. From the table, it is obvious that the intermediate subjects generated more basic science inferences than clinical inferences in both the cases. This pattern of deviation from the response pattern by beginners and seniors is known as the intermediate effect and has been reported in the literature on many occasions.13,46

Figure 3 shows the percentage of text propositions and inferences for Clinical Case 1. The percentages are based on the total number of propositions generated. The mean percentages of clinical text propositions generated by beginners, intermediates, and seniors were 61, 51, and 69 respectively. For Case 1, no significant interaction was found between the two types of propositions (text and inferences) and the level of training of the students, but there was a significant difference in the use of text propositions and inferences: $F(1,15)=5.41, p<.05$. The total mean inferences of clinical text of Case 1 were further broken down into clinical and basic science inferences. There was a significant interaction between the level of training and the two types of inferences generated: $F(2,15)=4.13, p<.05$. The beginners and intermediates generated more basic science inferences, whereas seniors generated more clinical inferences.

Figure 4 shows the percentage of clinical text propositions and inferences generated for Case 2. Intermediates generated more inferences than beginners and seniors, who, in turn, generated more text propositions than inferences. For spontaneous explanation of the clinical text for Case 2, there was an

Figure 2. Characterization of propositions generated by medical students in the explanation task
interaction between the level of training of the subjects and the use of the two types of propositions: $F(2,15)=4.00, p<.05$. There were also significant differences in the use of text propositions and inferences among the subjects: $F(1,15)=24.54, p<.0001$. As in Case 1, subjects generated more text propositions than inferences. On further parsing the total mean inferences into clinical and basic science inferences, there was an interaction between the two types of inferences (clinical and biomedical) and the level of training: $F(2,15)=4.39, p<.05$. Significant differences were also found in the generation of clinical and basic science inferences $F(1,15)=6.13, p<.05$. Overall, the intermediates and seniors generated more basic science inferences than clinical inferences in their explanation, whereas beginners generated more clinical inferences.

Overall, in their pathophysiological explanations, students relied mostly on the information in the text rather than generating their own inferences. Compared to Case 1, there was a drop in the total number of propositions generated for Case 2 with an average of thirty-three and twenty-five propositions respectively.

Figure 5 shows the semantic network of a fourth-year medical student after reading the clinical text. The student starts the case with the mention of the patient having Type 1 diabetes and complications associated with it. According to the subject, the infected ulcer might not have been the cause of the patient’s present and final disease, and further the clinical symptoms of grade fever and shaking chills pointed to septicemia rather than cellulitis as diagnosed. The subject discusses the effect of the last cellulitis treatment of the patient, which had required increased length of treatment, both IV and oral, at a higher dose.

The student mentioned how the patient’s earlier repeated treatment with antibiotics, which led to resistant bacteria, impaired the delivery of antibiotics to the tissues, and he discussed the failure of ticarcillin/clavulanate as antiobotherapy, which was identified as the wrong choice of drug. This student gave his own suggestion for an alternative treatment, namely adding gentamicin coverage. The subject did not give any pathophysiological explanation for the death of the patient, attributing it only to the untreated infection.

Table 2. Mean number of propositions used and generated from the clinical and basic science texts in the explanations of the two clinical problems by McGill medical students with different levels of training in the new curriculum, in 1999-2000, under two experimental conditions*

<table>
<thead>
<tr>
<th></th>
<th>Clinical Text</th>
<th>Basic Science Text</th>
<th>Clinical Inferences</th>
<th>Basic Science Inferences</th>
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<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
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<tr>
<td>Spontaneous Problem Solving</td>
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<tr>
<td>Case 1</td>
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<tr>
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<tr>
<td>Intermediates</td>
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<td>6.5</td>
<td>3.9</td>
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<td>Seniors</td>
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<td>5.5</td>
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<td>Case 2</td>
<td></td>
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<tr>
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<tr>
<td>Biometrically Primed Problem Solving</td>
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<tr>
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<tr>
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<td>4.8</td>
<td>3.4</td>
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<tr>
<td>Case 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginners</td>
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<td>1.7</td>
</tr>
<tr>
<td>Intermediates</td>
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<td>1.0</td>
<td>6.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Seniors</td>
<td>5.5</td>
<td>1.9</td>
<td>5.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

*In the first experiment, six students at each level (total=18 students) were given the clinical problem and asked to give a pathophysiological explanation of the Case 1. In the second experiment, the same students after giving the pathophysiological explanation were given the Basic Science text and asked to give the pathophysiological explanation again in light of the new information. The same scenario was repeated with Case 2.
Figure 3. Mean percent of text propositions and inferences generated from clinical Case 1 in the spontaneous explanation by students at different levels of training.

Figure 4. Mean percent of propositions used and inferred from clinical text of Case 2 during the spontaneous explanation by students at different levels of training.
In the written response displayed below, this fourth-year student generated a total of twenty-eight propositions in his explanation of the case, of which eight were biomedically related and the rest were clinical. This was the typical pattern of results for most of the fourth-year medical students.

The man has Type 1 diabetes mellitus with many complications thereof. Although the ulcer may well have been infected, it may well be that this was not the cause of his present and final disease. The high grade fever and shaking chills are less characteristic of simple cellulitis than of septicemia. Following or during his last “cellulitis,” which would have required increased length of treatment both IV and PO (~7-10 days IV) at a higher dose given that 1) his peripheral vasculature is so impaired and he is not delivering the RX to the affected tissues, and 2) his cell mediated immune system is somewhat impaired secondary to his DM and he cultured a resistant strain of klebsiella oxytoca in his wound that then proliferated.

Antibiotherapy was ineffective in controlling the infection because 1) prior antibiotherapy of subtherapeutic dosage and length of administration led to resistance; 2) his peripheral vascular supply causes him to have impaired delivery of antibiotic to tissues (i.e., he has a “functional abscess”); and 3) ticarcillin/clavulnate is not the drug of choice for gram negative bacillus coverage, even less so if this is a recurrent infection; gentamycin coverage in addition to the gram positive coverage with ticarcillin/clavulnate would have been wiser. The effectively untreated infection eventually became disseminated at first sporadically (thus the shaking fever) and then, overwhelmingly, leading to death.

Directionality of Reasoning. The results concerning directionality of reasoning in spontaneous problem solving are given in the upper portion of Table 3. The table presents the mean number of data-driven links, hypothesis-driven links, and elaborations for both the cases. From the table, we can observe that, for the spontaneous problem solving in both cases, more hypothesis-driven links were generated than data-driven links and elaborations.

For Case 1, in the spontaneous problem solving, no significant interaction was found between the three types of links (data-driven, hypothesis-driven, and elaborations) and the level of training of the students. However, differences were found in the use of three types of links: $F(1,15)=28.50, p<.0001$. Data-driven reasoning was exhibited less frequently than hypothesis-driven reasoning and elaborations.

In the pathophysiological explanation of the clinical text of Case 2, there was a significant interaction between the level of training of the subjects and the three types of links: $F(2,15)=5.68, p<.05$. There were also significant differences among the three types of links generated: $F(1,15)=44.77, p<.0001$. Beginners and intermediates generated more hypothesis-driven links, whereas seniors generated more elaborations.

Overall, students at all levels generated a greater number of links in Case 1 (data-driven, hypothesis-driven, and elaborations) than in Case 2, with an average of 9.6 and 5.6 links, respectively. This difference could be attributed to the fact that Case 2 seemed to be more complex. In informal conversations with students after the experimental sessions, they invariably graded Case 2 as more complicated than Case 1; however, they declared that both cases were within the limits of their knowledge.

Biomedically Primed Problem Solving

Use of Clinical and Biomedical Knowledge. The mean number of text propositions (clinical and basic science) and inferences from the students’ explanation of Case 1 and Case 2 are given in the lower portion of Table 2. It is obvious from the table that students generated fewer inferences and generated mostly text information. In general, there was a drop in the total number of propositions generated in the biomedically primed condition as compared to the spontaneous explanation condition.

Figure 6 shows the percentage of basic science text propositions, clinical text propositions, and inferences generated when providing the pathophysiological explanation for clinical Case 1. For Case 1, there was no significant interaction between the level of training of the students and the two types of propositions used. However, differences were found in the use of the two text propositions and inferences:
Figure 5. Semantic representation of pathophysiological explanation of clinical problem of Case 1 by a senior medical student when exposed to clinical text.
Subjects at all three levels of training used more of the information already available in the two texts rather than generating their own inferences. On further breaking down the total mean inferences into basic science and clinical inferences, we found no significant interaction in the generation of the two types of inferences and the level of training. Beginners and intermediate students generated more basic science inferences than clinical inferences, whereas the opposite was true for the senior students, who instead generated more clinical inferences than basic science inferences.

Figure 7 shows the percentage of text propositions and inferences for Case 2. As in Case 1, students at all levels were able to generate both basic science and clinical information from the two texts. In this biomedically primed explanation of the case, there was no significant interaction between the three groups of students and the two types of propositions used. However, differences were found in the use of text propositions and inferences by the students: $F(1,15)=92.55, p<.0001$. Like the trend set earlier, the two text propositions were used more than the inferences. Differences were also found in the use of clinical and basic science inferences: $F(1,15)=6.34, p<.05$, with the clinical inferences used more than basic science inferences by subjects at all levels of training.

Overall, in the biomedically primed problem solving, information available in the two texts (clinical and basic science) was used predominantly in comparison to the generation of inferences. There was also a drop in the total number of propositions generated from Case 1 to Case 2, with an average of fifteen and twelve propositions, respectively.

Figure 8 shows the semantic network after reading the basic science text of the same fourth-year medical student whose spontaneous explanation was seen in Figure 5. The student starts the case with pointing to the fact that since the patient’s immunity is altered and he has vascular disease, he is predisposed to infection. The patient’s repeated stays in the hospital have further increased his risk of harboring organisms that are drug resistant where this new information was added after reading the basic science text. Further, the past antibiotherapy provided a selective advantage to drug-resistant organisms. In the excerpt below, this senior student explains that an overwhelming sepsis occurred because the antibiotics had minimally affected the resistant organisms:

Due to his altered immunity and vascular disease the man is predisposed to infection of his ulcer and surrounding soft tissue. Repeated stays in the hospital have increased his risk of harboring drug resistant organisms (given the selective pressure present

<table>
<thead>
<tr>
<th>Spontaneous Problem Solving</th>
<th>Data-Driven Links</th>
<th>Hypothesis-Driven Links</th>
<th>Elaborations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td><strong>Case 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginners</td>
<td>4.2</td>
<td>1.7</td>
<td>13.5</td>
</tr>
<tr>
<td>Intermediates</td>
<td>4.5</td>
<td>2.6</td>
<td>16.0</td>
</tr>
<tr>
<td>Seniors</td>
<td>5.2</td>
<td>2.1</td>
<td>10.8</td>
</tr>
<tr>
<td><strong>Case 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginners</td>
<td>2.8</td>
<td>1.6</td>
<td>5.2</td>
</tr>
<tr>
<td>Intermediates</td>
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<td>1.6</td>
<td>10.2</td>
</tr>
<tr>
<td>Seniors</td>
<td>2.0</td>
<td>1.6</td>
<td>7.7</td>
</tr>
<tr>
<td><strong>Biomedically Primed Problem Solving</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Case 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginners</td>
<td>2.7</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Intermediates</td>
<td>3.5</td>
<td>1.9</td>
<td>5.7</td>
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<tr>
<td>Seniors</td>
<td>4.5</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Case 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beginners</td>
<td>4.2</td>
<td>1.7</td>
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</tr>
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<td>2.8</td>
</tr>
<tr>
<td>Seniors</td>
<td>1.3</td>
<td>1.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Figure 6. Mean percent of basic science text and clinical text propositions and inferences generated from clinical and basic science texts of Case 1 in the biomedically primed explanation by students at different levels of training. Students read the clinical text first, then the basic science text.

Figure 7. Mean percent of propositions used and inferred from clinical and basic science texts of Case 2 in the biomedically primed explanation by students at different levels of training.
in the hospital environment). Moreover, prior antibiotherapy with a first generation cephalosporin provided a selective advantage to resistant organisms capable of producing beta-lactamases/cephalosporinases constitutively. Administration of ticarcillin, even though in combination with clavulanic acid, was therefore a poor choice since the organisms had a high likelihood of cross-resistance to it. The resistant organism was therefore minimally affected by the antibiotic and this led to overwhelming sepsis.

Directionality of Reasoning. The lower portion of Table 3 presents data examining the directionality of reasoning in the explanation of Case 1 and Case 2 after exposure to the basic science texts. From the table, it can be observed that students made use of all the three types of directionality of reasoning in the biomedically primed explanations. For Case 1, there was no significant interaction between the types of directionality of reasoning generated and the year of training of the subject. However, differences were found among the three types of reasoning used: F(1,15)=4.85, p<.05, with elaborations used more than data-driven and hypothesis-driven reasoning by subjects at all levels of training.

In the biomedically primed explanation of Case 2, no significant interaction was found between the level of training and the types of links used. In this case, no significant differences among the types of reasoning generated were found; however, beginners and intermediates used more data-driven reasoning, whereas seniors used more hypothesis-driven reasoning.

In the biomedically primed explanation, students generated significantly fewer links than in spontaneous explanation, with an average of 3.4 and 7.6 links, respectively. This could be attributed to the fact that students at all levels of training were confident of their earlier explanation and did not feel the need to elaborate any further than what had been said in their spontaneous explanation. Informal conversations with the students support this explanation.

**Student-Generated Diagnoses**

Table 4 gives the list of causal agents generated by all students at different levels of training for the two cases. In Case 1, half of the beginner students made the general diagnosis of infection from gram negative bacteria, and the other half gave the correct diagnosis of septic shock. In general, the beginners, instead of explaining the reasoning behind the changes occurring, stressed more the antibiotic therapy given and the changes that should have been made for the therapy to be effective.

Case 1 was less complex than Case 2, which may help explain why, in general, students at all levels of training generated more elaborations in Case 1 than in Case 2 (i.e., they knew more about the first case than about the second). All eighteen students in Case 1 either completely or partially reached the correct diagnosis of Neisseria Meningitidis with septic shock.

**Summary of the Results**

In their explanations, students used mostly the information present in the text, with an average of about 75 percent from the text and 25 percent from their own inferences. The second-year students used an average of 83 percent of information already available in the text in their pathophysiological explanation, compared to 61 percent for third-year students and 76 percent for fourth-year students. The results are in keeping with results from prior studies showing that McGill students tend to rely on the information provided in the text rather than on inferences generated as explanation. In contrast, research results from a PBL school showed that students tend to generate a great deal more inferences, especially of a biomedical nature. In the present study, second- and third-year students generated more biomedical inferences, whereas their senior counterparts, the fourth-year students, generated more clinical inferences. Earlier studies of clinical problem solving

<table>
<thead>
<tr>
<th>Diagnostic Category</th>
<th>Beginners</th>
<th>Intermediate</th>
<th>Senior</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case 1</strong> (Diabetic Complication)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gram -ve bacteria from infection</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Septicemia</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Septic shock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Case 2</strong> (Meningitis)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacteremia</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Meningococcemia with septic shock</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Neisseria Meningitidis with septic shock</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Figure 8. Semantic representation of pathophysiological explanation of clinical problem of Case 1 by a senior medical student when exposed to the basic science text after reading the clinical text.
by health sciences students had shown the students’ heavy reliance on clinical inferences. In terms of the students’ reasoning patterns, the results were not completely consistent with prior studies, as there was an overall increased use of hypothesis-driven inferences as compared to data-driven inferences. However, students displayed data-driven reasoning in the primed condition, as the students had already spontaneously generated the basic science information in the text. In this regard, these students reasoned in a similar manner to students in the previous study. In this regard, these students reasoned in a similar manner to students in the previous study.

In the biomedically primed condition, students did not elaborate very much, as they had already explained in the spontaneous problem. There was a drop in the total number of propositions from an average of twenty-nine for the spontaneous explanation to an average of twelve after reading the basic science text. Most concepts present in the basic science text were used in the spontaneous condition, indicating the students had already integrated basic science concepts into their explanations.

Case 2 was more complex than Case 1. Students expressed that they had more difficulty with the second case; this is also evident in the student protocols. There was a drop in the total number of propositions used from Case 1 to Case 2, with an average of twenty-four and nineteen propositions respectively, an indication of how much they wrote about the case.

In the biomedically primed explanation of Case 1, more clinical text propositions were used than basic science text propositions with averages of eight and five propositions respectively. In Case 2 there was more use of basic science text propositions, with an average of six propositions compared to three for the clinical propositions.

**Discussion**

This article reports a study on the patterns of knowledge use and the deployment of reasoning strategies by medical students after the introduction of some aspects of problem-based learning in the curriculum. These changes included introduction of small-group, problem-oriented tutorials, which followed a series of lectures on the specific topic. The purpose of introducing such changes was to make it possible for students to maximize both the horizontal integration of basic sciences across disciplines and the vertical integration of biomedical and clinical knowledge. This double integration was assumed to promote the use of basic science knowledge in clinical problem solving, which we found to be lacking in previous studies. In our study, we focused on two aspects of medical students’ cognitive activity during clinical problem solving—namely, the generation of explanations and the use of reasoning strategies. Students from second-, third-, and fourth-year medical school were given two clinical problems and were asked to provide pathophysiological explanations of the problems. In this task, modeled after that used in the study by Patel et al., students displayed patterns of explanations with more elaborations and reasoning similar to the patterns of cognitive activity found in previous research (e.g., use of forward reasoning strategies), but with the addition of hypothesis-driven reasoning strategies.

In terms of knowledge utilization, medical students used more clinical knowledge and less basic science and pathophysiological knowledge in their explanations of the clinical cases. This finding is consistent with the 1993 study, which showed that medical students at McGill University, which then employed a conventional curriculum, made use primarily of clinical knowledge (e.g., patterns of association among signs and symptoms and hypotheses, such as diagnoses), when they are asked to provide the pathophysiology of a case. In the 1993 study, it was found that compared to students from the problem-based learning school, McGill University students solved cases using clinical knowledge rather than basic science or biomedical knowledge. It seems, then, that the efforts to foster vertical and horizontal integration into the curriculum do not preclude the utilization of, and reliance on, clinical knowledge as a way of explaining clinical problems. Comparative studies of expert and intermediate problem solving have shown that expert clinicians also make primary use of clinical knowledge to account for clinical problems and make use of biomedical knowledge only when confronted with difficult cases.

In our previous research, we have shown that students trained in conventional curriculum displayed more coherent explanations, whereas those trained in PBL curriculum generated less coherent explanations. These findings contradict those of Hmelo et al., which found the opposite results: PBL students producing more coherent explanations than conventional students. However, it is important to notice some critical differences in the way coherence is measured in the two cases. In our studies, we measure coherence in terms of the connectivity of the conceptual networks generated from the subjects’
protocols, whereas Hmelo et al. define it in terms of the number of relational operators that are chained in an explanation. Relational operators are equivalent to the links between concepts in a semantic analysis, often expressed as “verbs” in verbal protocols. In Hmelo et al.’s analysis, an explanation with more operators—that is, with a higher number of concepts that are connected—is considered more coherent than an explanation with fewer operators (i.e., with a shorter number of concepts). In contrast, our analysis regards the number of operators as irrelevant to the coherence of an explanation. For us, an explanation is coherent if there are no breaks in the inference chaining, regardless of the number of concepts that form the chain. Hmelo et al.’s notion of coherence is similar to our notion of elaboration, which we define in terms of the number of conceptual and inferential steps in an explanation. As in Hmelo et al.’s analysis, the longer the explanatory steps (i.e., higher number of relational operators), the higher the “elaborativeness” of the explanation.

In our present study, in terms of reasoning patterns, students used a mixture of hypothesis-driven and data-driven strategies. They began solving clinical cases by setting the problem in a descriptive manner (i.e., identifying the relevant signs and symptoms) in a data-driven-directed manner and then generating a hypothesis to account for the case. In contrast, students in PBL curricula typically use a pattern of reasoning that begins with the generation of several hypotheses, which are then used to account for specific clinical findings.26 It seems that McGill students educated in the hybrid curriculum, although using more hypothesis-driven reasoning than before, still maintain some form of data-driven reasoning at the beginning of their explanations. Although the extent to which this is beneficial has been challenged,29,39 our analysis in health sciences domains and those of others in various fields31,35-38,48 suggests that the use of data-driven strategies is an important aspect of complex learning.

A third issue that replicates previous research results is the presence in our data of the intermediate effect.39 The intermediate effect is shown when subjects at an intermediate level of training or expertise perform more poorly than expected, based on a model of learning that assumes that learning is monotonic: when learning progresses, the quality of performance increases linearly. According to this model, third-year medical students should perform higher than second-year students and lower than fourth-year students. What actually happened is that third-year students performed poorer in terms of both use of knowledge and deployment of strategies.30 We’ll share below our assumptions about why junior students struggled with this task.

Despite some similarities with the performance of medical students in previous research, we observed differences that we attribute to the changes in the curriculum with its emphasis on vertical and horizontal integration. Although the students explained both cases in clinical terms, most of the clinical propositions from their protocols were direct recall of text propositions, whereas the majority of their inferences were biomedical (i.e., there were more biomedical than clinical inferences). Biomedical knowledge helps glue the discrete clinical concepts to provide coherence to a medical explanation. Data-driven reasoning cannot facilitate this explanation, and thus explanation-based reasoning (based on hypotheses) is generated. Use of fewer basic science inferences by the senior medical students suggests that, at least in the more familiar clinical Case 1, they are able to consolidate their clinical and basic science knowledge into more coherent explanations without too much elaboration. In traditional medical education, such as parts of McGill, there is a large mentor-driven clinical exposure in the hospitals. We propose that it is this clinical exposure that helps facilitate the integration and corresponding ability to generate coherent explanations.

These findings can be explained as a result of the differential activation and integration of knowledge in the students’ memory and knowledge structures. As expressed in the construction-integration theory,51 comprehension results from the activation of two processes. First, there is a process where, in order to form a mental representation of a problem, a person (e.g., student) generates a number of concepts and propositions that somehow are related to the problem. This is done regardless of the overall coherence of such representation (i.e., regardless of whether it makes sense or not). This is followed by a second process in which the less-relevant concepts and propositions generated in the first phase are discarded, and only those that form a coherent representation are retained. We suggest that as the knowledge base of health sciences students increases with training (e.g., by learning more factual information), their ability to generate relevant inferences and to discard irrelevant associations also increases. This would account for the result showing an increase in inferences from the second to the third year of training, as seen in the number of propositions generated.
by the latter students. This would also explain the increase in explanatory coherence from third- to fourth-year students, because the latter have learned to “prune” their explanations of irrelevant concepts and propositions. Typically, beginner students activate, and therefore integrate, fewer concepts and propositions, given the smaller knowledge bases than those of intermediates and senior students. As training increases, students have acquired a great deal of both biomedical and clinical knowledge; as a result, they construct large explanations, as is the case with intermediates. However, their ability to prune such explanations, that is, to discard irrelevant associations, is lacking. Finally, the construction-integration theory also accounts for the performance of the senior students in the following manner: clinical experience serves to consolidate biomedical knowledge in practice situations, resulting in the students’ ability to integrate explanations into coherent structures and the learning of effective clinical knowledge and practice.13,27,52

Given that the same patterns of knowledge use and reasoning have been found in studies with the conventional and the modified curriculum, we may hypothesize that these patterns of performance development from beginner to intermediate to expert are universal characteristics of the cognitive performance irrespective of curriculum type. This is also supported by a study with residents in training who displayed the same performance pattern.53

Do students integrate basic science knowledge into their clinical explanation after being presented with the basic science text? Although students generated mostly clinical inferences, they did integrate some basic science information into their explanations of clinical problems. However, this integration decreased with training, with senior students generating far fewer basic science inferences than either beginners or intermediates, while increasing their clinical inferences. Similar patterns were found in both cases. It is important to note that most students spontaneously generated the concepts and propositions that were present in the basic science text. That is, they had already explained the cases using biomedical concepts in such a manner that, when they were given the basic science text, they felt no need to make many additional observations on the case. When the basic science text was presented, their problem solving was mostly data-driven, as they had already used many of the basic science concepts in the spontaneous explanation.

In conclusion, students enrolled in the new curriculum present many of the characteristics displayed by students in the previous curriculum, as analyzed in the earlier study by Patel et al.26 The similarities between the two groups of students consist of the use of similar types of knowledge (e.g., clinical) and reasoning strategies (e.g., data-driven). The differences are observed in the extent to which students integrate basic science knowledge and in the overall higher use of hypothesis-driven strategies in the spontaneous explanation (although they relied on data-driven reasoning in the basic science-primed explanation). In addition, although the students used more clinical knowledge, they made use of basic science knowledge in their explanations even in the spontaneous explanation condition.

Limitations of the Study

We acknowledge that the sample of participants in the study was small. This poses problems for the statistical generalization of the research results from the sample to the population. In order to make such generalizations, a statistically representative sample is needed. However, cognitive studies such as this one are based on a different approach to research, which does not rely on statistical generalization as a form of validity for its results. In cognitive studies, the goal is to characterize the knowledge structures and the reasoning strategies used by the participants, with the aim of developing a conceptualization of the cognitive processes involved. The key issue is then to provide evidence for the existence of a phenomenon, such as particular strategies or knowledge structures, not to determine how common such structures or strategies are.54 Cognitive research has allowed us, for instance, to uncover conditions related to the use of forward and backward reasoning and the nature of coherence in pathophysiological explanations in a wide number of research studies. It has also allowed us to uncover biological misconceptions held by medical students and to test a model of medical knowledge growth as exposed in Patel et al.13,27

In addition to the specific goal of cognitive research, protocol-based research (in which the main data sources constitute the collection and analysis of verbal data) is extremely time-consuming. It takes several hours to transcribe and analyze a single protocol. Therefore, it is not uncommon to find studies where the unit of investigation is not the sample, but a single subject55 or a small group of participants, as is the case in this study.
Implications for Dental Education

What does this all mean for health sciences education and specifically for dental education? As we pointed out earlier, an assumption in much of health sciences education is that the process of knowledge acquisition and skill increases linearly with training. The observed nonmonotonic learning process reported in this study does not support this assumption. The question is why this nonmonotonicity is observed. A hypothesis is that nonmonotonicity is an important characteristic of learning, as it allows the content learned to be consolidated in the students’ minds. In this light, the apparent decrease in performance of the intermediates is not necessarily solely an undesirable effect, but rather a necessary process of knowledge reorganization that eventually results in the further consolidation of knowledge. However, the fact that the process of knowledge reorganization exists does not necessarily mean that it should be allowed to take its course unchecked. Instead, this reorganization should be monitored so that unwanted consequences (e.g., a longer-than-expected reorganization process) can be avoided or prevented.

Although the medical task described in this article is a diagnostic task that, it may be argued, is not as relevant to dentistry as it is to medicine, the findings may be applicable to other clinical situations, such as disease treatment and management. As we pointed out in the introduction, a key component in any clinical task is the formation of a “problem schema” because the schema allows the clinician to be more efficient in providing for an explanation to the problem. Knowledge integration of underlying causal knowledge with clinical knowledge has a very important role in the development of such schemas by expert clinicians and in the appropriate generation of management plans, as has been demonstrated in previous research.24

In the case of health sciences education in general and dental education in particular, it appears that clinical knowledge can serve as a consolidating factor for previously acquired biomedical knowledge that fosters integration and reorganization in the context of use. The implications for dental education are manifest. One can anticipate that the dramatic growth of knowledge currently ongoing in the biomedical sciences will likely change the dental school curricula of the future,56 which may include increased teaching of the basic sciences, especially in the areas of genomics and molecular biology. It is important that the introduction of biomedical knowledge in the dental curriculum be informed by the experiences and, more importantly, by the educational and cognitive research taking place in other areas of health sciences education in order to optimize the efficient uptake of scientific knowledge by dental students—one that promotes vertical and horizontal knowledge integration.

In this context, problem-based educational components, such as small group sessions, can help bring to the forefront the implicit knowledge acquired through personal experience and through the problems of clinical practice (e.g., in clinics and hospitals). Also, by generating discussion in small group sessions, experiential knowledge can be linked to biomedical knowledge, which aids the integration of knowledge into coherent structures and consolidation of problem schemas, a characteristic of expert clinicians. This paradigm will hold true in any health sciences domain where students and practitioners must integrate basic science and clinical information. In this regard, improving education requires that educators know what can be expected of particular educational experiences. It appears that small group sessions can be used, not for imparting information, but for promoting knowledge integration as long as students elaborate on their experiences and knowledge previously acquired.23

In an extensive review of dental education, Hendricson and Cohen57 present an argument for implementing changes in dentistry by making substantial changes to the dental curriculum in response to changes in professional practice and the sweeping changes taking place in biomedical knowledge. Such changes point to an oral physician model of the professional dentist. The authors argue that innovative dental education should involve 1) a competency-based curriculum; 2) integration of dental education into the greater field of health and biomedical education; and 3) expansion of dental training to cover public health and prevention. Of critical relevance to our article is the increasing integration of biological and biomedical knowledge for dental practice, as new relations are discovered between oral health and major diseases needing multidisciplinary teams to tackle such problems. This will necessarily shift dental education and skill training from the types of treatments used in the past to new ones, in which basic biological sciences and pathophysiological knowledge play major roles.

The results of our investigations on the role of knowledge in medical education have important implications for the future education of dental students and the designing of curricula in schools of dentistry.
As shown previously, the relationship between basic science and clinical knowledge is not asymmetrical. Curricular design should take this relationship seriously because the kinds of clinical knowledge structures that are built on basic science are different from basic science knowledge structures built on clinical knowledge. Furthermore, the implementation of problem-based curricula in dental schools should be done by carefully looking at the effects of specific components of PBL on trainees’ knowledge and skill development.

With the increasing availability of powerful computer-based technologies that engage the student in active learning, such as simulations, students have the possibility of further consolidating previously acquired knowledge. Interventions in health sciences education can benefit from the judicious implementation of problem-based curricula in dental schools should be done by carefully looking at the effects of specific components of PBL on trainees’ knowledge and skill development.

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APPENDIX 1

Complete clinical and basic science text of Case 1 as given to the medical students

Clinical Text of Case 1
A 48-year-old man is admitted to hospital with a fever and an apparent infection of his right leg. He developed Type I diabetes mellitus at age 22 and has been insulin-dependent ever since. He suffers from severe diabetic retinopathy, severe diabetic peripheral neuropathy, severe coronary artery disease with Class III angina, chronic renal failure on hemodialysis, and recurrent cellulitis and ulceration of his lower extremities. Over the past two years, he has been admitted to hospital many times for multiple medical problems including three to four times for what has been diagnosed as cellulitis of his lower extremities. On these occasions he has been treated intravenously with broad-spectrum antibiotics for three to four days before being discharged from hospital on oral antibiotics of various sorts for an additional seven to ten days. On each admission, the area of infection was described as surrounding one or more of his chronic lower limb ulcerations. Specimens from his leg ulcers were taken on the second and fourth admissions and grew Klebsiella oxytoca resistant to ampicillin and sensitive to cefazolin, ticarcillin/clavulanate, ceftriaxone, ceftazidime, imipenem, ciprofloxacin, gentamicin, and tobramycin. No radiological or nuclear imaging of his legs has been done in the past two years. He was most recently discharged from hospital three weeks ago. He was treated with intravenous cefazolin for three days, then stepped down to oral cephalaxin for seven additional days and sent home. He mentions that he felt that his infection never really improved very much during or after his hospitalization, that his right foot then began to get more swollen and red over the past week, and that for the last three days, he has been having high fever, sweats, and shaking chills. His temperature is 40°. A large ulcer over his right medial malleolus is surrounded by severely red, tender, and swollen tissue. The ulcer is draining copious amounts of greenish pus. Gram stain reveals 4+ white blood cells and 4+ gram-negative rods. The patient is placed on intravenous ticarcillin/clavulanate. The following day the patient remains highly febrile and the area of redness around his wound is noted to be enlarging. His wound culture is growing 4+ lactose-positive coliforms and his blood culture is noted positive for gram-negative rods in both aerobic and anaerobic bottles. The dose of his intravenous ticarcillin is increased. During the evening of his second hospital day, he is noted to be becoming hypotensive and is transferred to the intensive care unit. Two hours later he has a cardiac arrest. Attempts to resuscitate him fail. The following day his blood and wound organisms are identified as Klebsiella oxytoca resistant to ampicillin, cefazolin, ticarcillin/clavulanate, ceftriaxone, and ceftazidime but sensitive to imipenem, ciprofloxacin, gentamicin, and tobramycin.

Basic Science Text of Case 1
Extended-Spectrum (Beta)-Lactamases as a Cause of Antimicrobial-Drug Resistance. Although there is a variety of mechanisms of bacterial resistance to (beta)-lactam antibiotics, the most important are the (beta)-lactamases, which are enzymes capable of hydrolyzing the (beta)-lactam ring of penicillins, cephalosporins, and related antimicrobial drugs, rendering them inactive. Much of the impetus to develop new (beta)-lactam antibiotics has been the emergence of bacteria that produce (beta)-lactamases capable of destroying existing antibiotics. First generation cephalosporins (for example, cefazolin/cephalexin) are susceptible to cleavage by a variety of (beta)-lactamases commonly found in gram-negative bacilli, including the chromosomal cephalosporinases of pseudomonas, enterobacter, and other genera, as well as the common plasmid-borne enzymes of Enterobacteriaceae. The latter enzymes also hydrolyze a variety of penicillins and, unlike the chromosomal cephalosporinases, are usually inactivated by (beta)-lactamase inhibitors such as clavulanic acid. Modifications of the structure of cephalosporins produced the cephamycins, including cefotetan and cefoxitin, which are resistant to many plasmid-mediated (beta)-lactamas. Further development resulted in the extended-spectrum cephalosporins ceftazidime, cefotaxime, and ceftriaxone, as well as aztreonam (a monobactam), which have better stability against many (beta)-lactamases. Because of their safety, efficacy, and favorable pharmacokinetics, the extended-spectrum cephalosporins have been used extensively. In the early 1980s, resistance to these drugs appeared in gram-negative bacilli with chromosomally encoded (beta)-lactamases, most often as the result of mutations that led to the constitutive production of these normally inducible enzymes. Enteric gram-negative bacilli with transferable resistance to extended-spectrum cephalosporins were first detected in the mid-1980s in Western Europe. The majority of these strains, predominantly Klebsiella pneumoniae, other klebsiella species, and Escherichia coli, were resistant to all (beta)-lactam antibiotics except...
cephemycins and carbapenems. This resistance phenotype was identified first in the United States and not long afterward elsewhere. Genes encoding these extended-spectrum (β)-lactamases were typically carried on self-transferable plasmids that often carried other determinants of antibiotic resistance. Studies of outbreaks of nosocomial infections with Enterobacteriaceae that produce extended-spectrum (β)-lactamases suggest that these strains arose in response to the selective pressure created by the use of extended-spectrum cephalosporins. Colonization and infection with these bacteria have also been associated with lengthy hospital stays, recurrent presence of patients in hemodialysis units, location in an intensive care or oncology unit, and catheterization of the urinary bladder. Molecular epidemiologic studies have suggested that there is dissemination of strains producing extended-spectrum (β)-lactamases within and between hospitals, as well as transfer of plasmids encoding these enzymes among strains. The optimal therapy for infections caused by organisms producing extended-spectrum (β)-lactamases is currently evolving. In studies of the treatment of animals with infections caused by Enterobacteriaceae that produce extended-spectrum (β)-lactamases, extended-spectrum cephalosporins were usually not effective, even when they were active against the organism in vitro. Imipenem or a combination of a (β)-lactam with a (β)-lactamase inhibitor was generally more effective. There have been no clinical trials of antimicrobial therapy against infections caused by bacteria producing extended-spectrum (β)-lactamases.

APPENDIX 2

Complete clinical and basic science text of Case 2 as given to the medical students

Clinical Text of Case 2

The patient was a previously healthy 17-year-old male transferred to the RVH with a two-day history of myalgias, arthralgias, and pharyngitis. On the evening prior to transfer, the patient developed a fever, increased myalgias, headache, and photophobia. The patient also noted a “blue-purple” rash on the face, trunk, and extremities. Physical examination prior to transfer revealed temperature 38o, BP 120/76, pulse 82, respiratory rate 16 and a toxic appearing patient with diffuse purpura lesions of 2-3 cm and small lesions on the conjunctiva and oropharynx. The fundi were benign. Nuchal rigidity was minimal. There were diffuse myalgias. The mental status was normal, reflexes symmetric, and Babinski sign absent. The remainder of the examination was normal. The initial labs showed a WBC of 3700 cells/µl, differential 51% polymorphonuclear leukocytes, with a platelet count of 105,000 cells/µl. The prothrombin time (PT) was 27.5 s, the partial thromboplastin time (PTT) was 98 s, the D-dimer assay was positive, and fibrin degradation products (FDP) >80 µg/ml (normal <10). Urinalysis showed blood, protein, and casts. The LP was normal. CSF, blood, and urine cultures were obtained. Broad-spectrum intravenous antibiotics were started (gentamicin 50 mg x1, ceftriaxone 2 gms q 24 hrs, vancomycin 1 gm q12 hrs). The following day the patient became hypotensive and was transferred to our hospital.

On arrival, the patient was alert and oriented. T: 37.6 o, Pulse: 124, Blood Pressure: 83/44, Respiratory rate: 12. The patient had a headache but no nuchal rigidity. The neurological exam was normal. There was diffuse muscle tenderness and a purpuric rash, with areas of purpura fulminans, over all of the body. The blood gas on 2 l/min oxygen by nasal cannula was pH 7.23, pO2 75, pCO2 42. Admitting labs showed a WBC 13,700 cells/µl, differential 68% polymorphonuclear; platelets 16,000 cells/µl, PT 21s, PTT 88s, fibrinogen 40 mg/dl (value is low), fibrin degradation products >80 µg/ml (value is high), Na+ 133, K+ 3.1, Cl- 97, HCO3- 15, Creatinine 260 g/l. The patient was initially managed with intravenous fluids and continuation of the same broad-spectrum antibiotics (gentamicin 50 mg x1, ceftriaxone 2 gms q 24 hrs, vancomycin 1 gm q12 hrs). Over twelve hours, the patient developed severe hypotension requiring dopamine, initially, and then norepinephrine to maintain the systolic pressure above 90. For several hours the systolic pressure was between 75 and 90 despite pressors. Over twelve hours, the patient developed severe hypotension requiring dopamine, initially, and then norepinephrine to maintain the systolic pressure above 90. For several hours the systolic pressure was between 75 and 90 despite pressors. During this period, the patient also developed oliguria and severe respiratory failure. In order to adequately ventilate, the patient was paralyzed and sedated. Nitric oxide was initiated at 20 ppm. On a FiO2 100%, pressure control of 29, PEEP 14, and rate 28, the blood gas was pH 7.18, pO2 89, pCO2 26. On right heart catheterization, the patient had low systemic resistance and low cardiac output. On chest x-ray there were new dense pulmonary infiltrates. The creatinine rose to 348 g/l. A NaHCO3 drip was initiated to control the metabolic acidosis.
After careful searching, gram stain of the buffy coat lymphocytes was found to contain intracellular gram negative diplococci. Later, gram negative diplococci, identified as Neisseria meningitidis, grew from the original blood and CSF cultures. High-dose penicillin G was initiated (2 million units i.v. q 6 hrs, dose reduced due to anuria). Because of concerns of Waterhouse-Friderichsen syndrome, the patient was started on stress steroids, 100 mg solu-cortef q 8 hrs. After 48 hrs, the hypotension and oxygenation improved. The renal failure was treated with continuous veno-venous hemodialysis (CVVHD), the disseminated intravascular coagulation (DIC) was treated with low dose heparin infusion (500 U/hr) and blood products (6 U of packed red cells and 28 U of combinations of platelets, fresh frozen plasma and cryoprecipitate). The microbiology laboratory further identified the organism as Neisseria meningitidis serogroup B. Over the next 96 hrs the patient's clinical condition began to improve. The FiO2 requirements began to decline. The DIC improved and the patient began to make small amounts of urine (5 cc/hr). Ten days after admission the patient was extubated. Dialysis was still required. The creatinine rose to740 g/l. The patient was tired but alert and oriented. A cosyntropin stimulation test (a measure of adrenal function) was normal. The patient was discharged 23 days after admission. The creatinine was 160 g/l. The patient was ambulatory but weak and there were numerous draining skin lesions. At follow-up two months later the creatinine was 100 g/l and all but two skin lesions had completely healed. Areas of anesthesia remained over some regions of previous purpura. The patient’s mental status was normal and activity level continued to improve. The CH50 (a measure of complement activity) was normal. Ciprofloxacin 500 mg p.o. was administered to eradicate the carrier state.

Basic Science Text of Case 2

Soluble mediators found in plasma from patients with severe gram-negative shock. Functional assays have been developed to study the inflammatory capacity of plasma collected from patients with severe gram-negative septic shock. In such assays, elutriation-purified, cryo-preserved human monocytes from one healthy donor are combined with plasma from patients with severe persistent septic shock for 5 h. Subsequently, the plasma is removed, medium added, and procoagulant activity (PCA) and secretion of tumor necrosis factor alpha (TNF-alpha) and interleukin 6 (IL-6) measured after 18-h incubation. Plasma from 10 patients (6 died) infected with Neisseria meningitidis previously shown to contain high levels of native lipopolysaccharide (LPS) (median 2,700 pg/ml), TNF-alpha, IL-6, IL-8, and complement activation products, had a low net spontaneous inflammatory capacity on the monocytes. The median levels of PCA, TNF-alpha, and IL-6 were 5, 0, and 4%, respectively, of the monocyte activities induced by normal plasma boosted with purified N. meningitidis (Nm)-LPS (2,500 pg/ml; net LPS-boosted capacity, 100%). The levels of PCA, TNF-alpha, and IL-6 obtained with plasma from shock patients were not different from those induced by plasma from 10 meningococcal patients without shock or with plasma from healthy persons. Boosting shock plasma with 2,500 pg/ml Nm-LPS had little effect on the monocyte activities since the median values of PCA, TNF-alpha, and IL-6 revealed a minimal increase from 5, 0, and 4% to 9, 2, and 6%, respectively. The shock plasmas revealed a strong LPS-inhibitory capacity that was largely absent in plasmas from 10 meningococcal patients without shock since the median levels of PCA, TNF-alpha, and IL-6 increased from 5, 0, and 0% to 135, 51, and 73%, respectively, after boosting with 2,500 pg/ml Nm-LPS. The LPS-inhibitory capacity was closely associated with the levels of IL-10. The median levels of IL-10 were 19,000 pg/ml in nine shock patients vs. 22 pg/ml in nine nonshock patients with systemic meningococcal disease. Removal of native IL-10 by immunoprecipitation restored the capacity of plasmas to induce monocyte activation either by native LPS or by boosting with Nm-LPS. IL-4 and TGF-beta were not detected in shock plasmas. In 24 patients with detectable meningococcal LPS (> 10 pg/ml, 0.1 endotoxin units/ml), the levels of IL-10 were correlated to the levels of LPS (r = 0.79, P < 0.001). IL-10 declined from initiation of antibiotic therapy and paralleled the levels of native LPS. Decreasing levels of IL-10 in serially collected shock plasmas were directly related to increasing monocyte responsiveness after Nm-LPS boosting. These results suggest that IL-10 plays a major role in containing activation of monocytes and possibly other LPS-responsive cells during overwhelming meningococcemia.