The process of problem-based learning: what works and why

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OBJECTIVES In this review, we portray the process of problem-based learning (PBL) as a cognitive endeavour whereby the learner constructs mental models relevant to problems. Two hypotheses are proposed to explain how learning is driven in PBL; an activation–elaboration hypothesis and a situational interest hypothesis.

METHODS Research relevant to these hypotheses is discussed. In addition, research studying the effects of various support strategies used in PBL is reviewed. Finally, we summarise a number of recent studies in which a new ‘micro-analytical’ methodology was used to trace the process of PBL in the natural classroom setting.

CONCLUSIONS We conclude that there is considerable support for the idea that PBL works because it encourages the activation of prior knowledge in the small-group setting and provides opportunities for elaboration on that knowledge. These activities facilitate the comprehension of new information related to the problem and enhance its long-term memorability. In addition, there is evidence that problems arouse situational interest that drives learning. Flexible scaffolding provided by cognitively and socially congruent tutors also seems to be reasonably effective, as opposed to ‘hard’ scaffolding represented by, for instance, worksheets or questions added to problems. Small-group work protects against dropout and encourages students to study regularly. Initially, students do not study much beyond the learning issues generated; the development of personal agency in self-study needs time to develop. The extent of learning in PBL results from neither group collaboration only (the social constructivist point of view) nor individual knowledge acquisition only; both activities contribute equally to learning in PBL.

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INTRODUCTION

In this article we review current knowledge about what works in problem-based learning (PBL) and why it works. We will not attempt here to review the entire literature on the topic; the database PubMed alone presents over 5000 articles that use the term ‘problem-based learning’ in their titles or abstracts. Nor will we make another attempt to review outcomes of PBL schools in comparison with those using conventional curricula. Curriculum comparison studies have been reviewed extensively over the past 20 years.\textsuperscript{1-6} Here, we will focus on reviewing studies that have examined what happens to the learner in PBL in order to elucidate the process that unfolds when students try to learn new material through this approach to learning. However, we must first establish which learning process we refer to. In an earlier paper, we suggested that there are at least three different perspectives on PBL in the literature: PBL as a ‘process of inquiry’; PBL as ‘learning to learn’, and PBL as a ‘cognitive constructivist’ approach, which defines the purpose of PBL as helping students to construct mental models of the world.\textsuperscript{7} Fortunately, all three perspectives concur on the following PBL-defining characteristics: (i) problems are used as a trigger for learning; (ii) students collaborate in small groups for part of the time; (iii) learning takes place under the guidance of a tutor; (iv) the curriculum includes a limited number of lectures; (v) learning is student-initiated, and (vi) the curriculum includes ample time for self-study.\textsuperscript{8-12} As only the cognitive constructivist approach has led to a sizable volume of research, we will confine our review to this interpretation.

In this paper we will first briefly describe the process of PBL, emphasising that it is a special way of acquiring knowledge of a domain. Secondly, we will interpret learning in this approach in terms of two hypotheses derived from cognitive psychology – the activation–elaboration hypothesis and the situational interest hypothesis – and review the evidence supporting these. Thirdly, we will look at research into the educational aids intended to support learning based on problems, including: the problems; the tutorial group; the tutor; scaffolds, and the self-directed learning activities of the students. Finally, we will discuss a number of recently conducted studies in which attempts were made to chart the learning process in PBL in the natural classroom setting using a micro-analytical methodology.

THE PROCESS OF PBL FROM A COGNITIVE CONSTRUCTIVIST POINT OF VIEW

The following description of the process of PBL will be brief because its constituent elements from the perspective of the cognitive constructivist framework have been sketched previously.\textsuperscript{7} In PBL, learners are presented with a problem in order to activate their prior knowledge. This prior knowledge is then built upon further as the learners collaborate in small groups to construct a theory or proposed mental model to explain the problem in terms of its underlying causal structure. As learners continue to study related resources, their initial mental model is further modified and refined. Moreover, as the learners’ preconceptions are activated, they become more easily able to identify gaps in their prior knowledge, thus enabling better learning to take place (the activation–elaboration hypothesis). Motivational processes support these cognitive changes. Situational interest is aroused by the enigmatic nature of the problem and acts as the motivating force that drives the learner to engage with the literature and to continue to seek relevant information until his or her hunger for new information related to the problem is satisfied (the situational interest hypothesis). These two hypotheses have been tested in a number of studies that will be reviewed in the next section.

EMPIRICAL EVIDENCE RELEVANT TO THE TWO THEORETICAL CLAIMS

In this section, we will summarise the evidence relevant to determining the mechanism by which PBL affects learning. Firstly, we will present studies relevant to the activation–elaboration framework. Secondly, we will review studies that relate to the emergence of situational interest in PBL classrooms.

The activation–elaboration hypothesis

The literature on the constructive nature of learning and the role of elaboration through self-explanation,\textsuperscript{13} discussion with peers,\textsuperscript{14} practising\textsuperscript{15} or responding to questions\textsuperscript{16} is extensive. What needs to be demonstrated here is that these processes are also vital to the process of PBL. This involves the review of a number of experiments designed to answer the following questions:

1 Does the initial discussion of a problem lead to the activation of previously acquired knowledge?
2 Is there evidence that having to explain the problem leads to elaboration?
3 Do these activities facilitate the comprehension and retention of relevant new information?

In a series of early studies that aimed to elucidate the role of prior knowledge activation and elaboration in the initial discussion of a problem, Schmidt and colleagues\(^7\) presented students who had studied the biological process of osmosis during high school with either a problem unrelated to osmosis or with the following problem: ‘A red blood cell is put in pure water under a microscope. The cell swells and eventually bursts. Another blood cell is added to a solution of salt in water. It shrinks. Explain these phenomena.’ When subsequently asked to recall whatever they remembered about osmosis, the students who had discussed the blood cell problem produced almost twice as many ideas about osmosis as the students involved in an unrelated task. This finding suggests that the initial discussion of a problem does indeed have a considerable effect on the activation and elaboration of previously learned knowledge. The authors were, however, unable to distinguish the influence of activation from the effect of elaboration (the students were prompted to explain) and nor were they able to exclude the possibility that the students simply learned from one another in the course of providing their explanations and thereby gained more knowledge.

To resolve these issues, De Grave \textit{et al.}\(^9\) compared the effects of small-group discussion of a problem with those of individual problem analysis and direct prompting for knowledge about osmosis. They discovered that small-group discussion had a larger positive effect than individual problem analysis; direct prompting for knowledge had the smallest effect. The assignment to explain leads students to further elaborate on their prior knowledge even in the absence of other students, but group discussion has a considerable additional effect, suggesting that elaboration on prior knowledge and learning from one another (even before new information is acquired) are potent means of facilitating understanding of problem-relevant information.

The text comprehension studies discussed so far had difficulty in studying effects of elaboration (through the explanatory activities required of the students) in isolation. To deal with this problem, van Blankenstein \textit{et al.}\(^11\) introduced a new research paradigm for studying the effects of elaboration in small groups on the learning of individual students. They taped a group discussion about a problem and presented this video to individual students. These students either only watched the video and listened to the discussion, or were prompted to actively provide explanations themselves a number of times while watching the discussion. In this way, the investigators were able to keep the information provided by other students constant over the conditions of the experiment (all participants saw the same video). Subsequently, both groups studied the same problem-related text for the same amount of time and were tested for knowledge twice: immediately and after 1 month. The authors found that immediately after studying the text, the elaboration group had a 28% higher score. After a month this difference had increased to 30%.\(^11\) It seems that elaboration in a small group not only facilitates the processing of a study text, but also adds to its longer-term memorability. This view is reinforced by other reports of the long-term effects of PBL.\(^12\)\(^-\)\(^14\)

The situational interest hypothesis

The situational interest hypothesis underlying PBL states that problems or puzzles create a desire in students to find out more about the topic, which leads to increased concentration, focused attention and a willingness to learn.\(^25\) Situational interest, as the term implies, is not a stable or dispositional form of interest, but is situationally aroused by an intriguing or captivating puzzle or problem. The psychological processes underlying this desire to learn can best be explained in terms of the incongruity hypothesis proposed by epistemic curiosity researchers (see Loewenstein\(^26\) for a review). Humans seem to have a natural tendency to wish to make sense of the world: when they encounter something they do not understand or something that violates their expectations, they experience situational interest because this state of affairs makes them aware of a knowledge gap between what they know and what they want to know. This phenomenon has been referred to as a cognitively induced experience of (knowledge) deprivation.\(^27\)\(^,\)\(^28\) This experience of deprivation initiates information-seeking behaviour intended to close the knowledge gap (i.e. learning occurs).\(^29\) As the knowledge gap closes, through the assimilation of new information into existing knowledge structures, situational interest decreases until the knowledge equilibrium is re-established.\(^30\)

Studies testing the situational interest hypothesis in the context of PBL are limited because situational interest has only become the focus of attention recently (but see\(^31\)\(^,\)\(^32\)). The central assumption of this hypothesis is that a problem presented in the context of learning arouses situational interest because it confronts students more extensively with what they
still do not understand. In turn, this perception of ignorance acts as a driving force to engage in learning. To test this idea, Rotgans and associates conducted a number of studies using a short rating scale that mentions the topic to be studied and consists of items such as ‘I want to know more about this topic’ and ‘I think this topic is interesting’. These studies tested the level of situational interest of students at several time-points, including on their arrival in the classroom, after a relevant problem had been presented and after some initial discussion about the problem. They demonstrated that the presentation of the problem significantly increased the level of situational interest in the students and this increase was maintained during the small-group discussion.

Soppe et al. investigated whether problem familiarity had an influence on student learning. In an experimental set-up, students worked with either a ‘familiar’ or an ‘unfamiliar’ version of the same problem. A measure of perceived problem quality was administered and outcome measures, such as the number of explanations for the problem put forward by the students, the quality of the learning issues derived from the discussion, the amount of time spent on self-study and the amount of knowledge gained as measured by a test were also obtained. The results showed that participants in the familiar-problem condition perceived the problem to be of higher quality than participants in the unfamiliar-problem condition. However, no significant differences in learning were found. The authors proposed that problems might be improved by making them more relevant to the everyday experience of students, an important consideration also stressed by others.

A number of studies have taken a more holistic perspective on the role of problems in PBL. These studies sought to determine the problem’s influence on learning in the context of other variables influencing learning. To this end, they tested causal models of PBL using structural equation modelling in which all key elements of PBL were included. They were able to demonstrate that problem quality (defined in terms of how clear the problem appears to students, its ability to stimulate interest and to trigger group discussion, etc.) as perceived by students is a major source of influence in PBL. Problem quality influences not only the quality of small-group discussion, but also time spent on self-study and interest in the subject matter.

Important of small-group collaboration

The cognitive benefits of small-group cooperation have been discussed extensively by various authors and need no further elaboration here. However, we would like to focus on three other aspects of the small-group tutorial. Firstly, the small tutorial group provides a platform for the development of friendships among students. Secondly, it enables closer contacts between students and teachers compared with those possible in a larger class. Thirdly, the regularity of small-group tutorials in the PBL environment generates peer pressure that is useful in motivating students to be diligent in their self-study and to meet the deadlines for work agreed by the group. These two non-cognitive side-effects of small-group collaboration have been found to be advantageous in preventing dropout from school and may be a reason why students in PBL...
curricula tend to graduate faster than students at conventional schools.\textsuperscript{50-52}

Role of the tutor

The tutor’s role in a PBL tutorial differs from that in a conventional tutorial. In PBL, tutors are expected to facilitate or activate student learning and to promote effective group functioning by encouraging the active participation of all members, monitoring the quality of learning and intervening when necessary.\textsuperscript{53-56} Tutors also play active roles in the scaffolding of student learning by providing a framework that students can use to construct knowledge on their own.\textsuperscript{57} Because it encourages students to think more deeply and offers some modelling of the types of questions students should be asking themselves during problem solving, the tutor–student relationship can be viewed as supporting a type of cognitive apprenticeship.\textsuperscript{10,58}

In view of this shift in the tutor’s role in the student-centred PBL process, many studies have sought to better understand how tutors contribute to student learning in PBL. One subject of considerable debate has centred around the importance of the tutor’s subject matter expertise: is it sufficient for tutors to have good facilitation skills or do they also need substantial knowledge of the subject matter? Results from several studies demonstrate that tutor expertise has a significant effect on student learning outcomes,\textsuperscript{59} whereas other studies indicate that it has no noticeable effects.\textsuperscript{60,61} One hypothesis that may explain this contradiction in findings is that the subject matter expertise of the tutor impacts on student learning more significantly when the cues and scaffolds within the problems and resources are insufficient to guide students in the process of identifying what is important to study. In such situations, students are more likely to depend on their tutor for guidance and thus a tutor who is more knowledgeable in the subject matter is of more benefit.\textsuperscript{62}

Another group of studies investigated the influence of tutors’ content expertise on the tutorial process. Silver and Wilkerson\textsuperscript{63} found that tutors with subject matter expertise were more inclined to play a directive role in the tutoring process, to speak more often and for longer periods, to supply more direct answers to questions posed by students, and to suggest more points for discussion. They concluded that these tutor behaviours might have a negative impact on the development of students’ skills in active SDL and also in collaborative learning. By contrast, Eagle et al.\textsuperscript{64} found that students with tutors who were content experts were able to generate more than twice as many learning issues for SDL and that these learning issues were almost three times more congruent with case objectives compared with those generated by students who were guided by non-experts. Moreover, compared with the latter group, students with content-expert tutors put in double the amount of time in self-study. Similarly, Davis et al.\textsuperscript{50} found no significant differences between expert-led and non-expert-led groups in terms of teacher-directed and student-initiated interactions, but instead demonstrated increased student achievement and satisfaction in groups led by experts. Both groups of authors\textsuperscript{59,64} suggest that the expert tutors, by virtue of their subject knowledge expertise, were better at posing questions at critical moments, thus positively influencing student learning. However, although the proficiency of content experts in using their subject matter expertise to direct student discussion has positive effects on student learning, their knowledge of when and how to use this expertise to facilitate learning is more beneficial. Thus, ideally, a tutor should be expert in both the respective subject matter and in facilitating student learning processes.

One theory of the effective tutor merges these two qualities.\textsuperscript{65} A key idea in this theory is the concept of ‘cognitive congruence’, which is defined as the tutor’s ability to express him or herself in the language of the students, using the concepts they use and explaining things in ways they can easily grasp. Schmidt and Moust\textsuperscript{66} suggested that both subject matter expertise and social congruence were necessary conditions for cognitive congruence to emerge. In this context, social congruence refers to interpersonal qualities such as the ability to communicate informally and empathically with students, and hence the ability to create a learning environment that encourages the open exchange of ideas. Thus, it was hypothesised that a tutor who is more socially congruent and better able to use subject matter expertise would be more cognitively congruent. Using structural equation modelling, the authors\textsuperscript{66} demonstrated that both social congruence and subject expertise influenced cognitive congruence, which, in turn, influenced tutorial group functioning and thus indirectly affected the level of student achievement by increasing the time spent on self-study. Social congruence directly influenced group functioning during the problem-solving process and the subject matter expertise of the tutor had a slight direct positive impact on student achievement. Hence, this study showed that effective tutoring that results in better student achievement requires the tutor to have both content knowledge and the ability.
to interact with students on a personal level, as well as to utilise language students easily understand.\textsuperscript{66}

Chng et al.\textsuperscript{67} hypothesised that tutors who exhibit more cognitively congruent behaviours would influence knowledge construction and acquisition at each learning phase in the PBL process. Thus, students who are under the tutelage of such tutors would be more extensively involved in the construction of knowledge (i.e. they would recall more relevant concepts in each PBL phase) and would ultimately achieve better results at the end of the learning process. Tutor behaviours were assessed by students and the tutors were subsequently divided into three groups according to their levels of subject matter expertise, cognitive congruence and social congruence. Student achievement at the end of the PBL cycle was measured using an essay test. An analysis of covariance (ANCOVA) using students’ pre-existing grade point average (GPA) scores as the covariate found that, contrary to the authors’ original hypothesis, only the social congruence of tutors had a significant influence on the students’ learning process.\textsuperscript{67} This effect of social congruence was evident in the total number of concepts recalled at the end of the PBL phases of problem analysis, SDL and reporting. No significant effects were found for the subject expertise and cognitive congruence of the tutor on any of the learning phases in the PBL process.\textsuperscript{67} (However, in line with the findings of Schmidt and Moust,\textsuperscript{64} all three tutor behaviours had a significant effect on final student achievement.) The results indicate that the social congruence of the tutor influences the learning process more substantially than cognitive congruence and subject matter expertise, at least in this educational context. The willingness of a tutor to establish an informal relationship with his or her students and to display an attitude of genuine interest therefore has significant impact. This is possibly because socially congruent tutors are able to create a non-threatening learning environment and to develop strong tutor-student relationships that support the open exchange of ideas and questions and promote student engagement in the learning process.

Some studies on tutors move away from investigating the tutor’s role in influencing student achievement alone and instead focus on the student learning process and issues such as how and when a tutor should intervene in the event of difficult incidents in tutorial groups.\textsuperscript{68,69} Himel-Silver and Barrows\textsuperscript{70} describe in detail how ‘collaborative knowledge building’ is facilitated. By analysing the discourse that took place between five medical students and their facilitator as they worked on a problem over 5 hours in two sessions, these authors demonstrate how the facilitator can support knowledge building through the use of open-ended questions that serve as scaffolds for students.\textsuperscript{70}

The use of scaffolds in PBL

From the descriptions above, it is clear that the role of the tutor as a scaffold to facilitate meaningful learning is one that is generally agreed upon. Although Kirschner et al.\textsuperscript{71} suggest that PBL is a minimally guided approach and is therefore less effective and efficient in helping students learn, others argue that PBL provides extensive guidance and scaffolding to help students learn.\textsuperscript{72,73}

The metaphor of scaffolding refers to the temporary support provided for learners to help them complete a task they would otherwise not be able to complete on their own.\textsuperscript{74} Although scaffolds can take multiple forms, Saye and Brush\textsuperscript{75} suggest that most scaffolds can be classified as either ‘soft’ or ‘hard’. Soft scaffolds are dynamic and refer to tutor actions that support specific learner needs, as described in the section on the role of the tutor in PBL.\textsuperscript{75-77} By contrast, hard scaffolds are static supports that can be developed in advance based on typically expected learner difficulties associated with a task.\textsuperscript{75} Such scaffolds can take the form of computer- or paper-based cognitive tools, such as worksheets.\textsuperscript{78} In line with the metaphor, scaffolds should gradually be withdrawn or fade out as the learner becomes increasingly responsible for his or her own learning.\textsuperscript{79} For example, although novices in a PBL environment may be supported initially with some resources that scaffold their learning, as their expertise increases, these students should be provided with fewer resources. In this way, students develop as independent learners through a form of flexible scaffolding.\textsuperscript{73}

Studies investigating the use and impact of hard scaffolds in the PBL context are rather limited. A study by Simons and Klein\textsuperscript{80} examined the impact of hard scaffolds on the learning outcomes of middle-school learners during the implementation of a PBL unit. Students were subjected to one of three experimental conditions, including one in which no scaffolding was provided, one in which optional scaffolding was provided, and one in which students were required to use all the scaffolds provided. Results showed that students in the optional- and compulsory-scaffold conditions performed significantly better than students in the no-scaffold condition. In addition, those in the compulsory-
scaffold condition produced better organised project notebooks containing a higher percentage of relevant entries. The PBL environment described in this study was one with very little consistent teacher support (soft scaffolding), in which students generally performed poorly. Simons and Klein\(^{80}\) therefore concluded that hard scaffolds seem to enhance student performance, especially under circumstances of limited teacher support.

Another study investigating the effect of worksheets as a scaffolding tool on student achievement in a PBL environment was carried out by Choo et al.\(^{81}\) Forty-eight teams (241 students) were randomly assigned to one of two experimental groups; students in one group were provided with a worksheet and students in the other group were not. No statistically significant difference emerged between the two groups in terms of their post-lesson concept recall tests. The findings of Choo et al.\(^{81}\) therefore suggest that scaffolds such as worksheets may not play a significant role in enhancing student learning within this PBL context. Furthermore, results from a survey administered to the students in this study indicated that the strongest factor to impact on their learning was the tutor, followed by the tutorial group; the worksheet was rated as having the lowest influence.\(^{81}\) Two other experiments have examined the effect of hard scaffolds in the form of questions provided as guidelines for self-study in addition to the problem.\(^{82,83}\) In one of these,\(^{92}\) the presence or absence of the scaffolds did not matter; in the other,\(^{80}\) scaffolding was even detrimental to achievement.

In conclusion, the effects of scaffolding in PBL are rather inconclusive and more research is needed here. Problem-based learning was originally developed in medical schools for use with relatively mature and motivated learners, a context in which hard scaffolds may have been of limited value. However, in view of the increasing implementation of PBL by educators of students at different levels of education and in various disciplines,\(^{84,85}\) research to shed further light on the role of scaffolding to support student performance in PBL is necessary.

Self-directed learning

Dolmans et al.\(^{86}\) examined the relationship between student-generated learning issues and self-study. As in an earlier study,\(^{38}\) they found considerable overlap between the learning issues identified by students and the faculty-intended objectives, but increasing this match by improving problem quality did not result in more self-study time. Therefore, they concluded that the learning issues produced during group discussion may not represent the only factors on which students base their decisions of what to study during self-study.\(^{80}\) Other factors may be involved, such as tutor suggestions, content covered in previous courses, literature found during self-study and the nature of the learning resources available. Interestingly, first-year students tended to focus on the learning issues agreed upon more than older students.\(^{80}\) It appears that students become more self-directed as the years of study progress. A similar finding was reported by van den Hurk et al.,\(^{87}\) who found that students in their first year of study adhered strictly to the learning issues, whereas in later years students pursued their personal learning interests to a larger extent. In addition, students who tended to study beyond the agreed learning issues spent more time on individual study and performed better on achievement tests.

As SDL is considered to be a key element in PBL, helping students develop the ability to regulate their own learning is an important priority. Some studies have demonstrated outcomes that can be considered to result from the emphasis on SDL in PBL. Students in a PBL curriculum have, for instance, been shown to borrow more books from the library than students in conventional curriculum schools.\(^{86-90}\) These findings suggest that PBL students are more independent learners and take more personal responsibility for their learning.

\begin{center}
\textbf{CHARTING PBL IN THE CLASSROOM}
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\begin{center}
\textbf{A micro-analytical approach to studying learning processes in PBL}
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Any attempt to study PBL as it occurs in its natural habitat – the PBL classroom – or to survey the underlying mechanisms of learning during PBL must seek new approaches to measurement. Conventionally, motivation and learning data are collected at the end of a course. These responses provide an ‘averaged’ impression of how motivated students were during the course or how much they learned. Although such a measurement approach is useful when the focus of interest is students’ overall motivation or learning, this type of measurement may hide important contextual variations during learning. The alternative approach involves carrying out detailed classroom observation: a learning event is videotaped and subsequently transcribed. Although this measurement approach tends to provide more detail on what is happening in a classroom, the
resulting qualitative dataset usually poses considerable technical and interpretational challenges.

In the subsequent sections, we present a series of studies on motivation and learning in PBL using an approach we refer to as *micro-analytical measurement*. In this micro-analytical measurement approach, a short questionnaire or a short knowledge test is re-administered several times at critical points during the course of a learning event. These repeated measurements are subsequently related to one another and to final outcomes of learning. Administering a measure several times over a learning event may provide insights into what actually happens during learning. From this, inferences can be made about the mechanisms underlying PBL.

**Interest is a driving force in PBL but is consumed over the course of learning**

In a study by Rotgans and Schmidt, a micro-analytical measurement approach was applied to investigate how students’ situational interest develops during PBL. Five short measures of situational interest were administered over the course of a 1-day PBL session. The first two measures were administered, respectively, immediately before and after the presentation of the problem to determine whether the problem would trigger students’ interest. The third measurement was conducted after the discussion of the problem and the generation of learning issues. The fourth administration took place after self-study to determine whether SDL activities had an effect on situational interest. The fifth and last measurement took place after the final discussion. The results of the study showed that once the problem had been presented, students’ situational interest increased significantly. However, as the learning event progressed, situational interest decreased: it seemed as if the initial increase in situational interest created by the problem was slowly consumed over the course of the learning event. The authors used the situational interest hypothesis to explain this phenomenon. The experience of being confronted with a problem that contains unknowns that need to be known triggers awareness of knowledge deprivation in the form of a knowledge gap that must be bridged by the finding of information about the unknowns. Knowledge acquired during self-study closes this gap. As situational interest is an indicator of the existence of such a gap, its decrease over time provides empirical support for this hypothesis. This study also showed that situational interest predicted students’ academic achievement with considerable accuracy, demonstrating that it drives learning.

In a follow-up study, Rotgans et al. (unpublished data) applied the same micro-analytical measurement approach to determine students’ situational interest in both PBL and direct instruction (DI). In a quasi-experiment study involving several classes of primary school pupils, the authors ensured that all factors were kept constant, except for the instructional approach. For instance, situational interest measures were administered at the same time-points to both groups, the same teacher was present, the same learning resources were available and the same amount of time was allocated in both groups. The results of this study revealed that the PBL group was consistently more interested than the DI group on all but two measurement occasions (Rotgans et al., unpublished data). Fig. shows an overview.

The first of these differences in interest occurred at the start of the session, just before the PBL group read the problem and the DI group was presented with some examples to demonstrate the application of the topic to a real-life context. This was to be expected because this time-point gave a measure of students’ situational interest before the treatment took place. Students in both conditions showed ‘equally little interest in the topic’. However, when students in the PBL group were presented with the problem, their situational interest increased significantly. After the problem had been presented, the level of situational interest in the PBL group decreased significantly, as in the study by Rotgans and Schmidt. In the DI group, situational interest decreased significantly from the start when the group was presented with some examples (instead of the problem). This outcome demonstrates that the DI group did not experience the positive surge in situational interest generated by the problem and the corresponding feeling of knowledge deprivation. Their interest decreased immediately from the outset. However, the DI group showed one significant increase during self-study, which occurred when this group was given the opportunity to engage in independent group discussion to discuss some real-life applications of the topic. At this time-point there was no difference in situational interest between the PBL and DI groups (Rotgans et al., unpublished data).

Overall, applying a micro-analytical approach to the study of student interest in PBL revealed the underlying situational interest processes, which would have been difficult to achieve with conventional survey measures or classroom observations. In the following study the micro-analytical measurement approach was applied to measure how students’
knowledge construction develops during the learning process.

Cumulative process of learning in PBL

The idea that learning is cumulative and that new learning depends on what has been learned previously is generally accepted by most educationalists. However, most of the evidence for this has come from experiments in psychology laboratories, particularly in the field of text comprehension. Yew and Schmidt argue that learning outcomes in PBL can only reflect collaborative processes because social constructivism suggests that knowledge is constructed through collaborative interactions and co-constructions. By contrast, it is also possible to infer that the individual SDL phase more significantly influences student learning in PBL, as studies on self-regulated learning have demonstrated that the use of self-regulated learning strategies strongly impacts on students' academic outcomes.

Yew and Schmidt therefore tested the hypothesis that PBL is cumulative and that learning in PBL involves both collaborative and self-directed learning. They also tested three alternative hypotheses: (i) only the collaborative learning phases influence learning in PBL; (ii) only the self-directed study phase influences learning in PBL, and (iii) both collaborative learning and self-directed study influence learning in PBL, but not in a cumulative process. The units of analysis used as an indicator of student learning at the end of each PBL phase were the relevant concepts recalled by 218 students at the end of each learning phase. These concepts, together with students' results in pre- and post-tests, were analysed using structural equation modelling. Results demonstrated that only the hypothesised model had a good fit with the data obtained. Fig. 2 shows an overview.

This model showed that students' prior knowledge significantly influenced learning in the first PBL phase (problem analysis), which then strongly influenced learning at the end of the SDL phase. Similarly, learning at the end of the SDL phase significantly impacted on learning at the end of the reporting phase. Finally, students' learning achievements were significantly influenced by learning at the end of the reporting phase. By contrast, results from the alternative hypotheses tested indicated that collaborative small-group learning or self-directed study alone were insufficient to account for learning in PBL. These findings also demonstrate that the sequential nature of learning in PBL (from the problem analysis phase to SDL to the reporting phase) is essential in influencing student learning outcomes.

DISCUSSION

We have sketched a picture of PBL that emphasises its cognitive constructive nature. We have reviewed empirical evidence supporting six propositions. The first is that the initial discussion of a problem in a small group of students leads to the activation of prior knowledge. This prior knowledge is elaborated upon to collaboratively construct a tentative theory explaining the phenomena described in the problem. The cognitive constructions that result from this exercise in the minds of these students subsequently
facilitate the comprehension of new information and its long-term survival.\textsuperscript{39}

Next, problems drive learning by generating situational interest. We have demonstrated that the introduction of a problem in the learning situation leads to an increase in situational interest in the topic at hand, and that this situational interest is largely maintained over the course of learning (although to some extent it seems to be ‘satisfied’ by the new knowledge acquired and diminishes over time). A higher level of situational interest, in turn, relates to higher levels of achievement.\textsuperscript{33}

Thirdly, as well as providing cognitive benefits, small-group tutorials contribute to students’ feelings of being ‘at home’ in their class, both socially and academically, and these protect against dropout. In addition, as these groups are focused on interaction in which students are expected to explain subject matter to one another, free riders are discouraged and students are encouraged to study regularly. This may be a reason why PBL curricula tend to have higher graduation rates.\textsuperscript{97}

Fourthly, tutors’ subject matter knowledge, ability to relate to students and ability to be cognitively congruent with students all contribute to learning in PBL. Findings in this area suggest that good tutors provide flexible scaffolding by supporting student learning on a ‘just-in-time’ basis. Experiences with so-called ‘hard’ scaffolds, such as those generated when worksheets or additional questions are supplied, were more equivocal; the few studies conducted in this area suggest limited effects and one even showed hard scaffolds to be detrimental to learning.\textsuperscript{81,83}

Fifthly, students in the PBL classroom have been shown to be more ardent users of library resources than students in conventional programmes, which suggests that these students are more self-directed in their learning. However, students need time to develop this propensity. One study showed that students at the beginning of PBL do not study much beyond the learning issues generated in the small group.\textsuperscript{97} Real personal agency appears to require time to develop, but when it does, it has surplus value over learning driven solely by external stimuli.

Finally, the extent of learning in PBL does not result from either group collaboration (the social constructivist point of view), or individual knowledge acquisition in isolation: both activities contribute equally to learning in PBL.

In summary, PBL seems to have fairly strong effects on learning and achievement compared with conditions in which learning is not driven by the presentation of problems. The studies reviewed generally showed learning gains in PBL students that extended beyond those in students in control conditions in which problems were not the focus of attention or in which students were not encouraged to elaborate on their prior knowledge. These findings seem to be at variance with the findings of curriculum comparison studies that generally do not report PBL to have effects superior to those of forms of conventional training.\textsuperscript{2} It seems that although effects are found at the micro level, these do not translate into visible effects at the curriculum level. This then raises the question of why this is so. What might explain this apparent paradox?

We can offer only some tentative hypotheses. The first is a ‘compensation’ hypothesis. There is some evidence that students who study under less favourable circumstances tend to compensate by working harder.\textsuperscript{98,99} This would imply that although students profit more from PBL, they compensate for this
additional support by working less hard. This is unlikely because students in PBL curricula tend to spend more time on individual learning than those in more conventional environments.

A second hypothesis, more parsimonious with the micro-level finding reviewed in this article, has been proposed recently. This hypothesis assumes that differential dropout and study duration mask the effects of PBL at the curriculum level. It takes as its starting point the observation that PBL curricula tend to show less dropout and shorter study duration than conventional schools. Comparisons between PBL and conventional schools may therefore be biased against PBL; effects of PBL become hidden by differential attrition and differential study duration. To test this hypothesis, Schmidt and colleagues (unpublished data) re-analysed 104 curriculum comparisons among schools for which dropout rates and study duration information were available. By correcting for differences on these variables, they were able to demonstrate robust effects of PBL on both knowledge attainment and diagnostic performance. It seems that micro-level effects of PBL do replicate at the curriculum level.

Given that well over 5000 studies referring to PBL are represented in PubMed, what interesting avenues remain for further research? We will confine ourselves to two suggestions here. The tutorial group, vital to the inner workings of PBL, remains in many respects a black box. For instance, differences in epistemological beliefs among students have been shown to influence achievement (i.e. students who believe that learning is knowledge construction perform better than other students). Why is this so? Are groups that are heterogeneous in terms of prior knowledge more successful than homogeneous groups, as some studies seem to suggest? Despite the importance in the small group of elaboration on what one already knows, students tend to avoid elaboration on the incorrect assumption that everybody in the group already knows what the individual knows. Would it help if tutors explicitly prompted for further elaboration? Tutors were shown to be more effective when they were able to explain things in a simple way. What does this imply? Do cognitively congruent tutors explain more items in the tutorial group? What would happen if tutors were instructed to explicitly provide scaffolds whenever their group reached a dead end in their discussion?

The second suggestion refers to long-term memory for what has been learned. Some literature implies that PBL has a particular effect on the long-term memorability of learned material, even if initially no effects are found. If this is true, there may be several reasons for it. For instance, as the problem that originally drove the learning will be stored in the memory along with the material learned, it is possible that such a problem acts as a cue for the retrieval of the knowledge acquired and thus increases its accessibility at a later stage. A related explanation may be that students in PBL organise knowledge in memory differently in a manner that facilitates its later retrieval. Studies of possible differences in knowledge organisation that affect the use of that knowledge in new contexts – the transfer issue – are virtually non-existent in education research, but are sorely needed.

In the Introduction to this paper, we suggested that different authors tend to define the ultimate goals of PBL in different ways. This paper took as its point of departure cognitive psychology and well-known principles of constructivist learning, with an emphasis on how people acquire knowledge. However, a point of view particularly prevalent in many medical schools tends to define PBL as a process of inquiry. From this perspective, the ultimate objective of PBL is to help students develop the ‘inquiry’ or ‘problem-solving’ skills of an expert by imitating his or her thinking processes. Working on a problem is seen as a simulation of what the doctor does, particularly in its emphasis on data gathering and interpretation. In this view of PBL, the role of knowledge acquisition is somewhat vague. Although most of its proponents acknowledge that knowledge is needed to fill gaps in the student’s knowledge base, from this perspective PBL is clearly focused on the acquisition of problem-solving skills. This perspective is attractive to medical educators because professionals in the field seem to think that their expertise is indeed partly based on the possession of such elusive skills. However, thirty years of research in this domain have made it clear that it is unlikely that problem-solving skills can be learned through education, or even that such things as problem-solving skills, independent of subject matter knowledge, exist. If this is true, it indicates that there are no shortcuts to acquiring expertise in medicine; that there are no domain-independent problem-solving skills the acquisition of which could compensate to some extent for lack of knowledge acquisition. The cognitive constructivist perspective on PBL incorporates this view that clinical reasoning is knowledge-based. It sees learning in the field of medicine as a series of attempts to construct mental models of the underlying mechanisms of disease in terms of how it is produced, the conditions under which it appears, and
its consequences in terms of observable signs and symptoms in patients. These mental models of disease, or ‘illness scripts’, are the cognitive tools that doctors use when they engage in clinical reasoning. The task of medical education is to help students develop these cognitive structures. Problem-based learning may be a useful way of doing so.

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