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Problem based learning: Cognitive and metacognitive processes during problem analysis

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Abstract. An important phase of problem-based learning in a tutorial group is problem analysis. This article describes a study investigating the ongoing cognitive and metacognitive processes during problem analysis, by analysing the verbal communication among group members, and their thinking processes. Thinking processes were tapped by means of a stimulated recall procedure. Verbatim transcripts of both the verbal interaction in the group and the recall protocols were analysed. The goal of this research is two-fold, i.e., to investigate whether PBL indeed leads to conceptual change and to develop a method that is sensitive to these phenomena.

The results suggest that the verbal interaction in a group shows only the tip of the iceberg of the cognitive and metacognitive processes on which it is based. The verbal interaction in the small group discussion mainly concerned theory building, and to a lesser extent, data exploration and meta-reasoning. Stimulated recall of the thinking process during that discusion, however, provides more and unique information about hypothesis evaluation and meta-reasoning. In the protocols of stimulated recall, the process of conceptual change by students could be made visible. The ways of dealing with anomalous data could be described as well as the conditions that determine how students deal with anomalous data. These results suggest that the method was sensitive for detecting conceptual change during problem analysis.

Cognitive and metacognitive processes in Problem Based Learning

Problem Based Learning (PBL)[1] is hypothesized to have a number of advantages over traditional approaches to teaching and learning, associated with the cognitive processes it is hypothesized to stimulate. For instance, Schmidt (1983; 1993) emphasized the cognitive effects of PBL in terms of knowledge activation and elaboration. In a recent review Norman and Schmidt (1992) presented empirical evidence for this claim. Despite the presumed importance of these cognitive and metacognitive processes, little is known about what actually happens and how problem-based learning in tutorial groups produces its positive effects. Some research has been done into the verbal interaction taking place in such groups (e.g., Schmidt, Spaay, & De Grave, 1988). Yet, insight into the nature of verbal interaction and participation by students is

insufficient to explain the effects of PBL; no simple causal relations exist. For instance, in a review of research on co-operative learning, Webb (1991; 1992) noticed that the less verbally participative students in a group can and do learn as well as the more prominent group members. She suggests that research into the cognitive and metacognitive processes itself is needed (see also Brown & Palincsar, 1989; O'Donnell & Dansereau, 1992).

Problem based learning can be seen as divided into several phases spread over periods of group work and individual study (Barrows, 1980; Schmidt, 1983). The procedure starts with identifying the problems in a case description or vignette. Next students engage in problem analysis. During this phase, students generate explanations for the problems found in the case. Based on this exercise students identify what they know and what they do not know of the issue at hand and make decisions about individual study. As a next step, this individual study is carried out and the results are reported to the group, after which a re-evaluation of the problem takes place. Not surprisingly, problem analysis plays a key role in problem-based learning. Schmidt (1993) conjectures that it serves at least four goals. First, it will help students mobilise whatever knowledge is already available. Activation of prior knowledge is important, because it focuses the learning effort and facilitates the understanding of new concepts to be mastered. Second, group discussion will help students to elaborate on their knowledge. The confrontation with the problem to be understood and with other students' knowledge of what might explain the phenomena will lead to enrichment of the cognitive structures of the participants. Third, the knowledge already available at this point becomes tuned to the specific context provided, i.e., the problem posed. Fourth, the discussion of a problem is supposed to engage the students in the subject to such an extent that epistemic curiosity is aroused to find out in more detail which processes are responsible for the phenomena described.

Knowledge activation and elaboration, discussion with other students and tuning of the knowledge to the problem students are working on, are not only preparatory work for individual learning, they are also instrumental in a more co-operative sort of learning resulting in restructuring of knowledge or in conceptual change. In other domains and in other educational contexts it has been shown that conceptual change is stimulated in situations that lead to dissatisfaction with the existing state of knowledge. In problem analysis the existing knowledge is questioned and evaluated, which should promote restructuring of that knowledge. According to Brown and Palincsar (1989), change is more likely when one is required to explain, elaborate or defend one's position to others, as well as to oneself; striving for an explanation often makes a learner integrate and elaborate knowledge in new ways. One of the main variables which can account for the advantage of social settings

is conflict in the group. Although social conflict can be an essential trigger, Brown and Palincsar (1989) emphasise that knowledge change is more the result of processes of co-elaboration and co-construction due to a shared cognitive conflict rather than to a social one.

A typical cognitive conflict, especially in an educational setting, results from a disagreement between existing knowledge and new, anomalous information. For instance, in daily life a marble and a feather simultaneously dropped from a height of two yards, will not hit the ground at the same instant. Yet, Newtonian physics laws predict that this will occur. How is that possible? Students can react to this situation in many different ways, ranging from disbelief to a radical change of mind. Chinn and Brewer (1993), who have reviewed the research about the role of conflict in promoting conceptual change, hypothesise that these differences are due to four cognitive attributes: The status of the anomalous data in the perception of the students, the characteristics of the prior knowledge, the students' perception of the validity and credibility of the new theory, and processing strategies. These cognitive aspects play a key role in whether a cognitive conflict is experienced and whether cognitive change will occur. Regarding prior knowledge Chinn and Brewer remark that the entrenchment of the prior theory, the ontological beliefs, the epistemological commitments and the background knowledge can result in a high resistance to change. Furthermore, a plausible alternative theory that is accurate as well, has a broad scope, is consistent, simple, fruitful and comprehensible is more easily accepted than a theory that lacks one or more of these qualities. The same applies to credible, unambiguous data stemming from multiple sources. These are more easily accepted than other data. And finally the processing strategies applied in the evaluation of anomalous data have different outcomes as far as theory change is concerned. Deep processing promotes such a change. Deep processing includes such mental processes as carefully attending to the contradictory information, attempting to understand the alternative theory, elaborating the relations between the evidence and competing theories and considering the fullest range of vidence. The specific combination of these four factors affects how students deal with anomalous data. Students may ignore anomalous data. They may reject these data. They may exclude the anomalous data. They may hold it in abeyance. They can also reinterpret the data. They can furthermore change their theory, but only marginally, or radically change their theory.

PBL can be perceived as a teaching and learning strategy that tries to induce cognitive conflict within students leading to conceptual change. This conflict results from a disagreement between the knowledge of the individual students and the problem they are working on. In fact, this is an axiom of PBL. A problem should be designed in such a way that there is a mismatch or at least

a gap between the students' knowledge and the problem. The way students deal with this conflict will be largely due to this discrepancy. Alternative theories are not provided by the teachers, but are constructed in the small group discussion, based on a combination and evaluation of the knowledge of all group members and verified later during self study and report. The success of this enterprise will be very important; if no plausible theory can be constructed, conceptual change will, as yet, not occur. The other two factors will probably play a less important role. Credibility of anomalous data will be high as far it is data presented in the block book or by the tutor; data brought forward by group members will be perceived differently. Finally, the way students are trained to work with these data. The 'seven-jump' in Maastricht or the 'triple jump' in MacMaster, guarantees a deep approach to the problem.[2]

The purpose of the present study is two-fold. The main issue is to investigate whether PBL indeed leads to conceptual change. Since conceptual change itself (not the factors leading to it) is essentially an intraindividual process, a method must be developed that is sensitive to these phenomena. Following the suggestion by Webb (1991), a stimulated recall method was used and the resulting protocols were analysed using a zooming-in technique that first focused on the more macroscopic features of the protocols, and was followed by a more microscopic analysis of the dynamic aspects of the protocols. Finally, the seven ways of dealing with anomalous data, described by Chinn and Brewer and ranging from ignoring anomalous data to radical change of theory, and the factors they are dependent on, were used to analyse a protocol of an individual student at a more detailed level, searching for traces of conceptual change. As a consequence of this dual purpose of the study, the present article has both a methodological and a theoretical aspect. These are dealt with separately.

Method

Subjects

A small tutorial group was formed by five second year students of the faculty of medicine of the University of Limburg (Maastricht). These students were well versed in PBL, having analysed problems in a tutorial group meeting in twice-weekly sessions for about two years. Third and fourth year medical students (5 in total) acted as interviewers in the stimulated recall session. These students received a special training for this task. The interviewers had the relevant background knowledge about the case that was analysed.

Materials

The problem (case) they had to analyse was a case taken from the block "Pain" which is part of the third curriculum year. It was a difficult enough problem to stimulate the students' cognitive processes. On the other hand, the students also had sufficient prior knowledge for analysis of the problem.

> Case: A painful ring finger
> Marcus B is a 34 year old factory worker. He has never visited his GP for this complaint before. On a few occasions in the last months he had noticed painful, episodic red cords on both forearms. His left ring finger was particularly hurting, especially when it was cold outside or when he was working with cold materials. The colour of this finger then changed from white to blue and red and after some time it returned to normal again. In the last week the pain had become so severe that he decided to visit his GP. Marcus is a heavy smoker (40 cigarettes a day); his GP had already warned him that this could harm his health.

The case is about a not very common disease called 'thromboangiitis obliterans'. The disorder is characterized by an inflammation and occlusion of the small- and medium-sized arteries and veins in the hands, forearms, feet and legs. This disorder develops most frequently in men under the age of 40, especially Asians and individuals originating from eastern Europe. The cause of thromboangiitis obliterans is not known. There is, however, a definite relationship with cigarette smoking. Thrombosis of the vessels is likely the primary event, leading to an intense inflammatory response. This inflammation results in fibrosis around the blood vessels, leading to obstruction of the blood flow. The most common symptoms are cramps in the arms or legs. Another common symptom is episodic ischemia (decrease in bloodflow to a tissue resulting in lack of oxygen) of the fingers or toes following exposure to cold. It manifests itself as pain and the colour changes described (called Raynauds's phenomena). A third common finding is thrombophlebitis in the superficial veins. In Figure 1 the formal knowledge about thromboangiitis obliterans is related to the information in the case.

Procedure

The tutorial group analysed the problem during 20 minutes. The discussion was chaired by one of the students. They were seated in a semi-circle. The group interaction was recorded on video tape in a professional video-studio, with two separate rooms, one for the recording and one for the technical staff. Subjects in the tutorial group were instructed to deal with the case in the way they would do normally. They were told that the video recordings would take

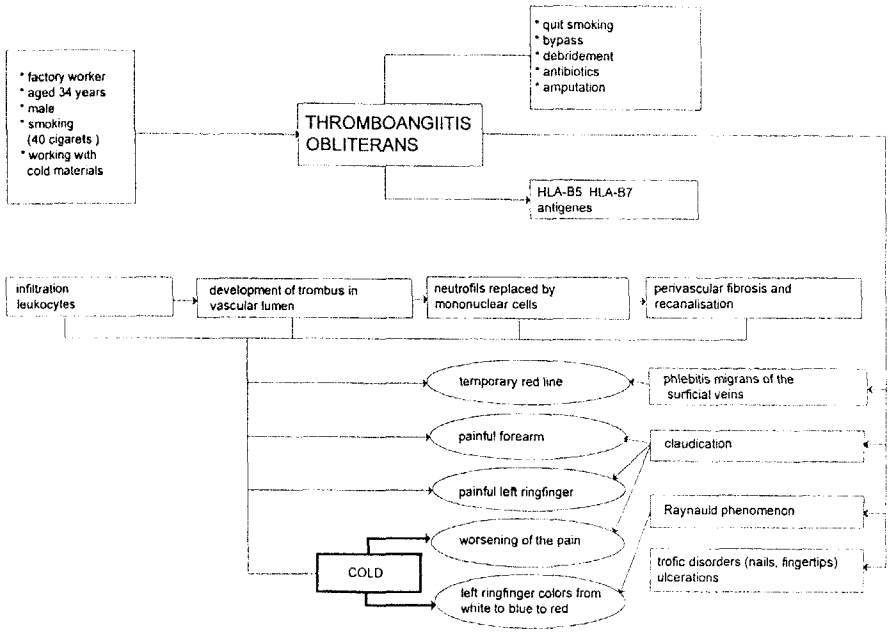

Figure 1. Content structure of the case: A painful ring finger.

about 20 minutes, but that they should not worry about time. They would be told when to stop the discussion.

The interviewers were assigned to the individual members of the tutorial group before the problem analysis took place. During the problem analysis they observed the group (especially the student they were assigned to) on monitors in the video-studio.

Immediately after the session had been completed, five identical copies of the master tape with timecodes were produced. In the meantime the interviewers and the subjects went to five nearby small rooms for the stimulated recall. These rooms were equipped with video playbacksystems and audiotaperecorders. The interviewer introduced him/herself and explained the stimulated recall procedure. After two minutes the videotapes were delivered in the recall rooms and the recall procedure started. The students were invited to tell all they could remember of their own thinking process during the discussion. The video tape was played back to help them to remember. Each time an episode reminded the student of something (s)he had been thinking during the discussion the videotape was stopped. This could be done by the student or by the interviewer. The task of the interviewer was to stimulate the subject to verbalise the thinking processes during the recall situation. The stimulated

recall session was recorded on audiotape. After this had been completed, the subjects were briefly interviewed about their experiences during group work and stimulated recall.

Analysis

A verbatim transcript including a time code was produced of the videotape of the tutorial group and of the stimulated recall of the four group members. Due to equipment failure no protocol of the discussion leader could be produced. The resulting protocols were analysed into clauses. In order to classify these clauses a coding schema originally developed by Hassebrock and Prietula (1992) had been adapted. The original schema especially applied to individual diagnostic reasoning. The same cognitive processes could be recognized in shared diagnostic reasoning or problem analysis in a tutorial group. In order to include the social aspect of the task, the category Process Level, with two subcategories had been added. Some categories had been simplified; data exploration and interpretation have been combined into one category.

Analysis of the protocols was done by two research assistants in a consensus procedure. An example of such a protocol analysis of a stimulated recall protocol is given below(Excerpt of student A):

> Yes, there I was already thinking about his smoking (code 2.1) / Yes, blood vessels and smoking might have something to do with it (code 2.2) / two packages a day is rather much (code 2.1) / It was mentioned in the case in such a way that it must have to do something with it (code 2.1) / I was wondering how long it is lasting (code 2.1) / He is only 34 (code 2.1) / and how long ago did that GP mention that (code 2.1) / but to continue on that I did not find too relevant (code 1.1).(time:one minute and fifty two seconds)

Results

This figure shows that the verbal interaction and the stimulated recall protocols contain the same categories of cognitive processes, but in different proportions. This applies especially to: Group procedure (1.1), group cooperation (1.2), theory evaluation (2.3) and metareasoning (2.4). Apparently, the students tend not to express these cognitive processes, especially where they value the contributions of others and where they reflect on their own prior knowledge and their learning process. The verbal interaction protocols show only the tip of the iceberg of these phenomena; hence the stimulated recall protocols are needed to gain more insight into the processes and conditions for conceptual change.

Table 1. Coding system for protocols of both verbal interaction and stimulated recall during problem analysis.

Process level	Task level	Non-task level
1.1 procedure 1.2 cooperation	2.1 data exploration: problem definition; reference to the information in the case; identification, structuring, integrating and initial interpretation of information; signalling lacking data 2.2 theory building: causal reasonings; hypothesis; associations specification; generalisation. 2.3 theory evaluation: confirming evaluation; non-confirming evaluation; evaluation about certainty. 2.4 meta reasoning: reflections on prior knowledge; reflections on the learning process; reflections on strategy of thinking.	3.1 irrelevant

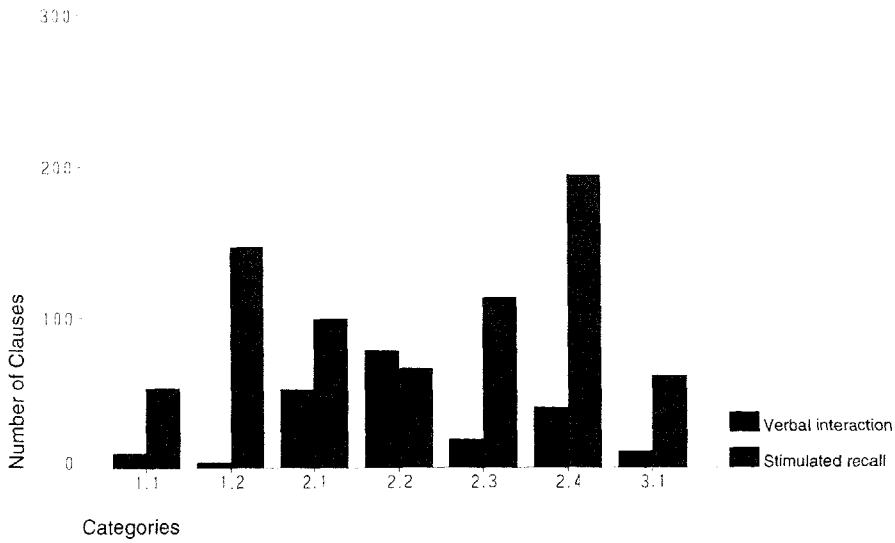

Figure 2. Analysis of the verbal interaction and the stimulated recall: frequencies of clause types.

Only one category, theory building, is more prominent in the verbal interaction than in the stimulated recall; little additional information can be found in the stimulated recall protocols. This means that the content of the verbal interaction gives a good impression of the causal reasoning that is going on. However, in this experiment only a fairly small group was used. If the group had been larger, the ratio of theory building in the verbal interaction and theory building in the stimulated recall might have been less outspoken, since

only one student can talk at a time, while each one can have his/her own ideas and deliberations. Data exploration is also a prominent category in the verbal interaction.

It is interesting to see that thinking about procedures and about co-operation in the group is an important part of the tacit cognitive processes of the group members. Furthermore, it is difficult for students to be constantly task-oriented. Especially the stimulated recall protocols show how students can be "daydreaming" like this excerpt of student D shows.

> I am trying to follow the discussion, but it is hard for me to concentrate. I am writing with my left hand and I am drawing a flower. I am thinking of a girl who was drawing flowers always. Then I am looking at the blackboard just to participate in the discussion again. (time: nineteen minutes)

This analysis of the protocols as a whole into categories only provides a static picture of the cognitive and metacognitive processes in problem analysis. The time-codes provide the opportunity for analysing the twenty minutes stream of thought as well. Here we present the temporal analysis of the category of theory building. Theory building was selected because it is most prominent in the verbal interaction. Furthermore, research on the effects of co-operative learning (Webb, 1991; 1992) suggests that variables related to explanation (at a verbal level) are very important for learning effects.

Theory buiding can be stimulated or inhibited in a group process. During discussion the frequency of theory building can increase or decrease. Figure 3 illustrates this pattern.

Remarkably, the two patterns for interaction and stimulated recall are rather similar. This figure becomes more comprehensible when the development of the content during the 20 minutes is investigated on the basis of Chinn and Brewer's framework.

During the first two minutes the group defined the problems to be analysed. Four problems were identified: 1. What is the cause of the red cord?; 2. Why is that left ring finger painful and cold due to cold material or cold wetter; 3. Explain the colours; 4. What is the relation with cigarette smoking?

From the third until the eighth minute the group generated explanations for the problem of the red cord over the forearm. The group members constructed several theories to explain this phenomenon. First, there was the theory about blood poisoning (sepsis); next, a theory about lymphangitis came up, and finally, there was a theory about stenosis. In the course of the discussion there was increasing agreement about 'stenosis' as an explanation for the patient's problems.

From the eighth minute on, the group started to work on the second problem (the relation between pain and cold). To explain these symptoms the students

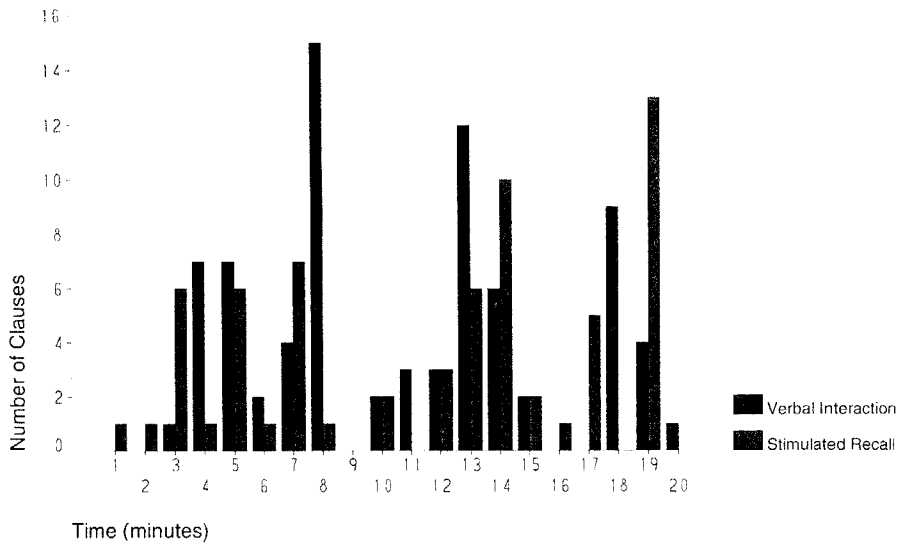

Figure 3. Frequency of theory building in the verbal interaction and the stimulated recall per time unit (minute).

elaborated on stenosis, where they talked about the combined effect of stenosis and vasoconstriction on the blood vessels. They also generated explanations about the different colours (problem 3). At this time a great many explanations came up (see Figure 3). From the ninth until the thirteenth minute, the students continued thinking about the colours and returned to the red cord. Now they came up with the idea of an inflammatory reaction, and the relation between inflammation and stenosis. Two of the students returned to the idea of sepsis. In this phase there was some confusion and not too many new ideas came up.

From the 13th minute on the group continued with explaining the colour change and linked it to smoking and stenosis through the concept of lack of oxygen. In the 14th minute they tried to be more specific about the relation between smoking and stenosis. After generating these ideas they noticed lack of knowledge and in the sixteenth and seventeenth minute again there was no real progress. The students were thinking about the left ring finger, had some associations with background knowledge, but did not really generate explanations for the symptoms. In the 18th minute they returned to the relation between the left ring finger and the red cord. In the nineteenth minute they briefly attended to the possible influence of the working conditions of a factory worker. In the last minute the chair summarized the discussion and ended the group meeting.

During this discussion the students seemed to go through a process of conceptual change. This is exemplified in the next excerpts of the stimulated

recall protocols. One student was very explicit in her conceptual change. Therefore we will use her stimulated recall for a more detailed analysis of the factors affecting conceptual change, but now and then we will add excerpts of the stimulated recalls of other students. These excerpts extend from the third until the eighth minute, a period in which theories are generated to explain some of the data and in which the students tried to find the right track for further elaboration.

The content of the verbal interaction and the stimulated recall are both printed next to one another to facilitate comparison. Sometimes these excerpts are interrupted by comments to show the relation of the excerpt with the framework of Chinn and Brewer.

start: two minutes and fifteen seconds

Verbal interaction in the group	*Stimulated recall of student A*
E. Problem one, the red cord C. Artery maybe B. Yes we learned something about blood poisoning	Then they talked about blood poisoning. And then I even more began to think about what was the word. And what was the mechanism. [.....] I was even thinking of the literature I had studied then, but I could not remember. It was a surgery book I think, about wound healing. I knew we had learned about it. And then I want to know that. I remembered that case, that red cord and that rusty nail and that he had been constructing the gate and then he got that inflammation which completely went through that arm. All the time I am sitting to think about it.
E. Lymphangitis B. A kind of inflammation A. What was that? E. It was an inflammation of the lymphs. An inflammatory reaction which goes to the lymph. Lymphangitis and then one gets a red cord.	Yes there I thought "That's not it". I knew that lymphangitis .... It did not sound real. No, I was trying to find the word 'sepsis', then everybody knows what I mean. About those lymphs. I did believe that, any way that they had something to do with it. But his story was not really convincing.

End: three minutes and two seconds

This excerpt shows the influence of the factor background knowledge on the way student A reacted to the data. The case reminded her of an earlier case on sepsis, although she could not find that word. Her reaction to the story regarding the lymphs is illustrative for the form of "holding anomalous data in abeyance". The ideas about lymphangitis conflicted with her ideas. She did accept part of the data, but did not yet explain the data. By placing this in abeyance, student A's initial theory remains unaffected. Yet with abeyance,

the individual assumes that this theory will be articulated later on so that it can explain the data. Later in the verbal interaction, and in the stimulated recall, student A tried to articulate her theory.

start: three minutes and two seconds

Verbal interaction in the group	*Stimulated recall of student A*
D. But that red cord, is it over the length of his arm ?	
C. Yes I think so	
A. But the information in the case is different	
B. A episodic red cord (reads aloud)	
D. It seems logical, but there is no information about it in the case	
A. What was the name of blood poisoning?	
A. We have learned about it in a block. But that was about inflammation last year. With that nail and construction working ...	
C. Oh yes	
A. He got an inflammation at his thumb which became red.	
C. but that was far more acute	Yes then I thought that does not fit altogether. But I kept thinking about that. This is the moment I am starting to doubt. It was not the same. The red cord was, however, it was caused by something else. But how we did not know. It was generated over several months and the other thing was very acute. So it can't be completely the same
A. Yes	
C. In the course of months	
A. In a few of months	

End: three minutes and fifty seconds

Here student A very clearly recognised a conflict between her initial theory and the anomalous data presented by student C. The anomalous data was very credible and unambiguous, because it was information found in the case description; it had quite some influence in the theory building of student A. This data about the episodic and acute nature of the symptom had been ignored at first, but now it had to be explained. However, as yet there is no viable alternative theory, so student A did not change her theory.

start: three minutes and fifty seconds

Verbal interaction in the group	*Stimulated recall of student A*
C. Maybe it is a stenosis of a blood vessel, because he smokes so many cigarettes and when it becomes cold it becomes even narrower.	
D. Does not that redness refer to an inflammatory reaction? With a stenosis it will withdraw. Yes, I think one does not get a red cord	Yes, then I agreed with student D. A stenosis does not generate a red cord. First, I thought that it can't be possible, but later I thought it could. That smoking has a clear relation with it. I was writing these things down: stenosis of a blood vessel, the redness which resulted from an inflammation. I tend to forget that lymph while it must have something to do with it; and that stenosis of the blood vessel will surely return in the discussion.
C. Yes A. Yes	
C. Yes maybe an accumulation of waste products	

End: four minutes and twenty two seconds

Student C introduced an alternative theory of stenosis but student D confronted student C with anomalous data and thereby confirmed the theory of student A. The anomalous data were considered very credible and student A was already in doubt. That she did accept the data was demonstrated by what she was writing down.

start: four minutes and twenty two seconds

Verbal interaction in the group	*Stimulated recall of student A*
A. Why only his forearms B. Maybe it will affect his legs E. By the way it is both his forearms A. Yes both forearms A. Why only his forearms? [.....]	Yes I did not understand that. Why only his forearms. If he had it on his legs then it would be mentioned in the case. Someone says: Maybe he does have it on his legs, but he can't see it because he wears trousers. Then I thought yes but it is painful and he would feel it and also when he would undress in the evening he would see it, but that did not seem of any importance. It must have something to do with that forearm, that is no coincidence. [.....]. I did not believe that stenosis completely, but it must have something to do with it. I did not believe that the red cord was caused by that stenosis. I was thinking don't be too quick with that stenosis. I was not completely against it. Especially when she told that story of the father of her friend. Then I thought Yes it can be true. It was a plausible story, but you can't explain everything with it.
C. Doesn't it have something to do with his smoking ? I mean two packages a day has a clear influence on the blood vessels. C. Maybe a strange example, but the father of a friend of mine has had balloon angyoplasty at a certain moment because his two fingers were also completely cold. They did balloon angyoplasty, because his blood vessels were completely blocked.	
D. Where exactly did they do this? C. In his upper arm	

D. So a stenosis of a blood vessel
A. A stenosis or a thrombus
B . stenosis
D. Yes that's a .....
B. But you don't get a red cord ?
A. No I don't understand that completely, that red cord. That his fingers become red, okay
B. The fact that those fingers become cold and painful I can accept too.
E. The colours of that finger one can explain that. If there is no blood .....
A. But why only his ring finger. He has it on both forearms, so one would expect left and right.

I am constantly playing with my fingers. I want to explain the mechanism. I was constantly thinking of the left finger. Then she said. Where did they do that procedure? Yes in the upper arms, but these are his forearms. Something I will really study well: why those forearms?

End: six minutes

Student A was presented with multiple anomalous data provided by the alternative theory of stenosis. However, there were some weak points in the alternative theory. The scope of this theory was not broad enough to accept it ("... but you can't explain everything with it"). Another problem with the alternative theory was a lack of an explanatory mechanism which is an essential ingredient in a plausible alternative theory. Student A did accept the data (..."it can be true") but noticed a lack of information about the mechanism. In the next part of the protocol of the stimulated recall this searching for a mechanism is very clear.

Verbal interaction in the group

Stimulated recall of student A

<intermezzo; students are talking about the ring finger and make some irrelevant remarks>

start: six minutes and fifty seconds

C. Shall we continue ?
E Yes so .....
C; But that red colour whether that can be caused by that stenosis, I don't know. Maybe some products stay behind so that one gets a certain reaction and the waste products cannot be removed sufficiently, or something like that.

I was thinking about that. I did find that a fine story about those waste products and the mechanism behind it. Then it all fitted somehow. It was not all clear, but it was all reasonably plausible.

A. Yes but then there is that lymph. Then the story is complete. Waste products which stay behind.

C; Yes okay but what name you give it
B. Yes but what kind of waste products
A. Yes I don't find it real plausible.
C. It's only a brainstorm.

Those waste products, but what kind of waste products. It did have something to do with it. It was not really plausible, but on the other hand it was. As a matter of fact that is beginning to overrule the other ideas. Its true, but when B said: Which waste products ? I did not know either. I was not really convinced. I am a bit in-between. But I think everybody was.

End: seven minutes and twenty three seconds

This excerpt shows a conceptual change in student A ("as a matter of fact that is beginning to overrule the other ideas"). The alternative theory became plausible when in the last part of the excerpt an explanation was given for the red colour: the story about the waste products and the mechanism behind it. Student A also had the impression that a kind of group theory was developing. This impression was supported by the stimulated recall of another student, D.

Verbal interaction in the group

Stimulated recall of student D at about the same time slot

I thought we all had it reasonably clear, all of us. When we started with the case I thought there won't be any progress. Now I think we did make quite some progress.

Another characteristic of the quality of the alternative theory is its fruitfulness. In other words, if it can generate new explanations for other data. In the protocols of the students it became evident that when they started to explain the next problem they used this theory and elaborated on it. In Figure 3 it is evident that it was fruitful in the sense of generating new ideas (e.g., in the 8th minute).

The use of this theory and the further elaboration of it can be identified in the protocol of the verbal interaction.

Verbal interaction in the group (eight minute)

D. I think that the blood vessel is narrowed by a plaque or something like that or just more narrowed. When it is cold, vessels are more constricted, so the blood supply will be less and then maybe there is a complete obstruction of that ring finger. Yes why only that ring finger I don't know. But there is an obstruction and then it becomes white.
C. Yes and it can be painful because of the waste products. Anyway there is no sufficient blood supply.
D. The waste products won't be removed and then maybe there is an inflammatory reaction and then that red colour.

This part of the problem analysis vividly shows the diverse cognitive and metacognitive processes. Figures 4 and 5 numerically summarize these findings. Comparing these graphs suggests that much covert metareasoning precedes an increase in overt theorybuilding.

Discussion

The goal of this research was two-fold, i.e., to investigate whether PBL indeed leads to conceptual change and to develop a method that is sensitive for these phenomena.

Regarding the methodological objective of the study, the data found suggest that the combination of an analysis of the verbal interaction and of the stimulated recall protocols obtained immediately afterward provides an instrument for the investigation of individual cognitive processes taking place during PBL sessions.

There are several aspects of this method which support its validity. First, videotaping the problem analysis did not affect the students' discussion.

Student C: "At first I thought that it would be a rather artifical situation for brainstorming, but I didn't find it different from what normally happens in a tutorial group".

Student D: "I was rather well concentrated, I did not have the idea: Oh there is a video, not at all"

Furthermore, the fact that the stimulated recall took place immediately after the problem analysis kept subjects involved in the cognitive process.

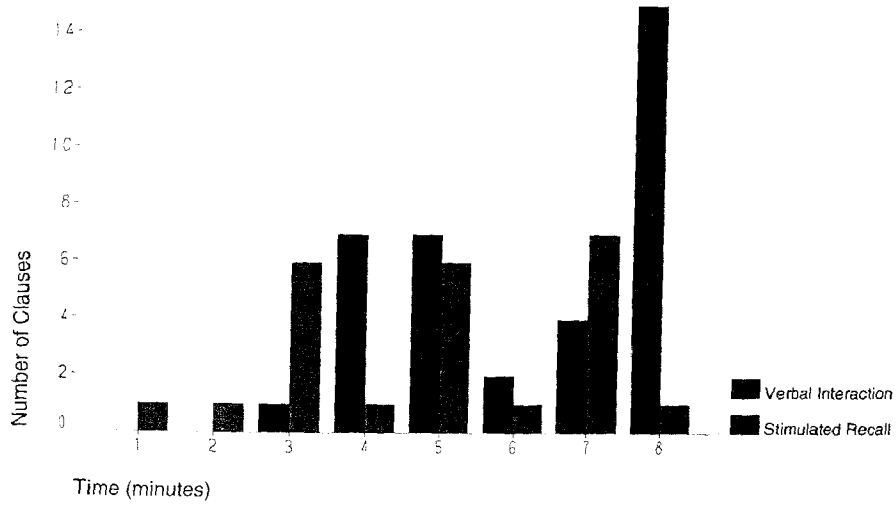

Figure 4. The process of theory building during the first eight minutes.

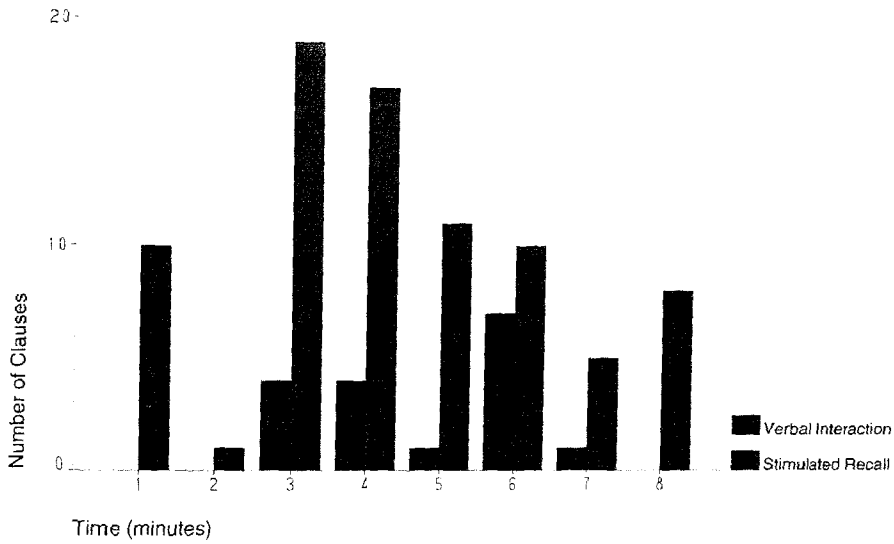

Figure 5. The process of meta reasoning during the first eight minutes.

Student B: "What I found really funny, was that one relives that situation, thoughts are coming back, but emotions as well. What I found funny then, I still found funny. It is a rather profound experience."

Student C: "It really struck me what one still knows about what one has been thinking. First I had some doubts about that, but one can remember it all. "

Another pertinent characteristic of this method is that the verbal interaction, to which students are asked to respond, has some features of a think aloud protocol. The social interaction situation, however, imposes constraints on that interaction: not everybody can reveal her thoughts at the same time and some things are better not said in public. In the succeeding stimulated recall session the students are encouraged to fill in these gaps. Many studies that use the stimulated recall method miss this opportunity to 'fill in' aspect, and thereby lose valuable data.

A fourth characteristic of this method, suggesting that these protocols give valid data about the cognitive processes, is the concurrence between the verbal interaction and the stimulated recall protocols of the individual students, and especially the fact that certain intra-individual phenomena (metareasoning) precede certain other phenomena in the verbal interaction (theory building). An example of this effect is found in the comparison of Figures 4 and 5.

In research on teacher thinking (Yinger, 1986), where stimulated recall is often used, several problems were found with this method, e.g. the frequent use of generalisations and justifications by subjects, which were not directly linked to the actual situation. In the protocols in the present study, very few of these were met. Generalisations were rarely made by the students, and they were, however, closely related to the thought process. The next excerpt provides an example.

Student B: "Then I thought, there are often things mentioned in a case, which have nothing to do with it and which often steer the group off the right track, that might apply to this case" (time: fifteen minutes and fifty seconds)

As far as we know, this study has been the first to investigate cognitive processes in a PBL session. As has been mentioned already, it is hard to say whether the magnitude of the findings and the ratio of category scores in the verbal interaction protocols and the stimulated recall protocols will vary with the group size. It probably will, since group size constrains the number of clauses per student in the verbal interaction, but does not affect that number in the stimulated recall protocols.

The theoretical question of how students deal with anomalous data and whether PBL results in conceptual change can be answered in a positive sense. It must, however, be remarked that the classification of protocol clauses was sometimes difficult. Students give information about the acceptance of the data, but they very often do not explain the data they accept, making it difficult to make the finer discriminations suggested by Chinn and Brewer, e.g., between exclusion and rejection of anomalous data. Our analysis of

the protocol of student A suggested that her cognitive representation of the case at hand changed dramatically during the shared analysis of that case. Starting with a commitment to an initial explanation of sepsis, student A was constantly presented with anomalous data. Her first reaction to these anomalous data was to hold it in abeyance. Later on, data were accepted, gradually leading to acceptance of a new theory which was constructed at that time, leading finally to conceptual change.

The protocol of student A also reveals insight into factors that affect how people respond to anomalous data. The factor 'prior knowledge' stands out clearly. Background knowledge (knowledge learned previously) exerted a great influence on the construction of explanations. Due to some observational similarities (red cord) between the background knowledge and the case it was difficult for some students to let it go. The entrenchment of the prior theory was not very strong. Ontological beliefs and epistemological commitments did not play a recognisable role. This combination of features of the prior knowledge may explain why student A could give up her first explanation, to which at first she seemed sincerely committed. The research reviewed by Chinn and Brewer predicts that a change in knowledge to which one is sincerely committed, is hard to procure.

Another factor that influenced student A's responses to anomalous data is the characteristics of the alternative theory. The excerpts showed that the availability of an alternative theory, the mechanism of the alternative theory and the quality of the alternative theory (especially its scope, simplicity and fruitfulness) played an important role in giving up old ideas. It is not clear whether the accuracy and consistency of the alternative theory also played a role.

The characteristics of the anomalous data itself were also a factor which influenced how student A dealt with anomalous data. How students deal with anomalous data also depends on the *source* of the anomalous data. The stimulated recall protocols sometimes included remarks about the credibility of the other group members' contributions. Another characteristic of anomalous data was its ambiguity. In problem analysis the data is not always unambiguous. Furthermore anomalous data can be multiple data. This characteristic is especially important because in a group discussion the possibility of presenting multiple data is great. There is often more and different knowledge in a group, so that a student can be presented with multiple views and hence multiple anomalous data. In the excerpts presented, multiple data gradually falsify particular objections she had made to earlier data.

A final factor that affects an individual's response to anomalous data is the strategy of an individual for processing the anomalous data. Deep processing

promotes conceptual change. In the excerpt of student A, it is evident that this deep processing is activated.

This study only investigated the cognitive change processes going on in the problem analysis phase of PBL. These processes can and will extend over the later phases of self study, report and evaluation. Processes of change that have started out in the analysis phase, but that have not yet resulted in a substantial alteration can proceed in this phase. Uncertainty about the theories or explanations students have constructed may require such a thing. Due to this uncertainty alternative theories are not dismissed completely but have to go through an extended phase of verification during self-study.

The results of the quantitative analysis of the protocols provided us with more knowledge about the cognitive and metacognitive processes during problem analysis. It provided information with respect to when, where and how often different (meta)cognitive processes occurred both at the level of verbal interaction and at the level of stimulated recall. It appeared that information derived from both the verbal interaction and from the stimulated recall complemented each other in providing a more complete picture of these processes during problem analysis.

The framework of Chinn and Brewer could be used for the analysis of the protocols. In the excerpts of the protocols several ways of dealing with anomalous data could be identified as well as most of the factors which determine how students deal with such anomalous data. It appeared that the students generally were very open towards other group members regarding the construction of explanations. Problem analysis has an uncertainty raising effect on students. It can be concluded that using this framework provided more information about the more important moments of conceptual change.

Notes

1. In this article the abbreviation PBL will be used when referring to the educational system or philosophy. When writing about the learning process itself we will use the full term.
2. The concepts 'seven jump' and 'triple jump' are used for describing the steps in the problem solving process. These procedures are used to improve the effectiveness and efficiency of this process.

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