It's all about metacognitive activities: computerized scaffolding of self-regulated learning
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Discussion and conclusion

This thesis focused on the development of a computerized scaffolding system to dynamically scaffold students’ self-regulated learning and examined the effects of this system in small groups. In this conclusion, we discuss our findings answering the central research question: What are the effects of computerized scaffolding of self-regulated learning on learning of collaborating students? We performed two experimental studies to address this question. The main findings were discussed in three parts that shifted from specifying the effects of scaffolding towards understanding how scaffolds contributed to students’ learning in a social setting. In part I, we discussed the rationale for the design of our scaffolding system and the results of the first study on scaffolding self-regulated learning in dyads. In part II, we discussed the results of the second study on scaffolding triads’ metacognitive activities with different forms of scaffolds (structuring vs. problematizing scaffolds) and elaborated on the current understanding of scaffolding during collaborative learning. Finally in part III, we further specified how metacognitive activities were embedded in the interaction among group members and how scaffolding influenced this. This work contributes to the knowledge on scaffolding, self-regulated learning, metacognition and the socio-cognitive perspective on collaborative learning in educational sciences. On a practical level it should enable refinements to computerized scaffolding systems based on an attention management system.

Part I. Computer-based scaffolding of self-regulated learning

Up until now there have been very few examples of personalized e-learning solutions which adapt to the learners' needs, even though we know that personalized education is more effective than standardized education (Bloom, 1984). Scaffolding is defined as providing learners with support when needed and fading assistance as the student’s competences increase (Wood, Bruner & Ross, 1979). Nevertheless, computer interpretation of students' competences is problematic, especially in ill-structured domains (Woolf, 2009). This is why we chose a different approach in the Atgentive project\(^\text{11}\), in which we developed our computerized scaffolding system. An attention management system was used that focused on capturing learners’ attentional focus. This information was the source for deciding when to support learners with scaffolding.

In chapter two we addressed the sub-question: How can an attention management system enable dynamic scaffolding of self-regulated learning? In order to answer this question, a conceptual framework was created based on theories of scaffolding, attention and self-regulated learning (Molenaar & Roda, 2008). This conceptual framework guided

\(^{11}\) The Atgentive project was an European STREP under the sixth Framework program. Atgentive stands for “Attentive Agents for Collaborative Learners”. The objective was to investigate the use of artificial agents for supporting the management of the attention of young or adult learners in the context of individual and collaborative learning environments.
the development of our attention-based scaffolding system called AtgentSchool that applies the central elements of scaffolding (diagnosis, calibration and fading). The system uses an attention management system which derives information from the student’s environment to model the attentional focus of the student with observable events (diagnosis). The attentional focus is compared to the logical attentional focus based on the learning assignment. This comparison is the basis for the selection of the scaffold (calibration) that either supports the current focus or guides the learner to a different focus. Finally, scaffolds are only sent when the student seems to need the support (fading).

An intervention model was defined based on self-regulated learning theory to select appropriate scaffolds. This model formulated metacognitive, cognitive and motivation scaffolds. The selection of metacognitive scaffolds was based on the cyclical model of Zimmerman (2002), which indicates when different metacognitive activities are used to control and monitor students’ learning: orientation and planning before commencing the task, monitoring and evaluation during the task. The selection of cognitive scaffolds is largely dependent on students’ own ability to ask for help using the help button in the interface. Finally, the selection of motivation scaffolds is related to the groups’ motivational input using interface buttons. AtgentSchool is a combination of an attention management system and the learning environment Ontdeknet. In AtgentSchool the scaffolds are communicated to the learner by a 3D embodied agent. The first test runs confirmed that the system provides dynamic scaffolds and students appreciated the scaffolding. This gave the green light for the first study.

In the third chapter, we presented the results of the first experimental study with the AtgentSchool system. The second sub-question was addressed: What is the effect of computerized scaffolding of self-regulated learning on learning outcomes and perception of collaborating students? A control group (n=54) was compared to an experimental group receiving scaffolds (n=56) working with the AtgentSchool system for 6 lessons (4.5 hours). The assignment was to learn about another country from an inhabitant of that country to decide if you want to live there and to write a group paper. We measured the effect of dynamic computerized scaffolding of self-regulated learning on dyads’ performance (the quality of the paper the dyads wrote), individual domain knowledge (knowledge test) and the dyads’ perception of the learning environment (questionnaire). The results showed that dynamic scaffolding had a significant small to medium effect on the performance of dyads, which is in line with other research on scaffolding of self-regulated learning (Azevedo & Hadwin, 2005; Azevedo, et al., 2008). However, no effects of scaffolding were found on the students’ domain knowledge. The absence of effects of scaffolding on the students’ domain knowledge is in line with other scaffolding studies, which also failed to find an effect of scaffolding on domain knowledge (Bannert, 2006; Bannert et al., 2009; Lin & Lehman, 1999).
The dyads’ perception of the learning environment was measured in the middle of the assignment and at the end. Dyads in the experimental group reported more positive perceptions of their teacher and of the collaboration, both during and at the end of the learning sequence. Conversely, with respect to the perception of the software and of the 3D-agent, students in the control and experimental group did not differ significantly at the same measurement. There was an interaction effect, dyads receiving scaffolds perceived the software and 3D-agent as more useful in the middle than at the end of the lesson sequences compared to the control group. A possible explanation could be that dyads give more positive evaluations of the environment at the beginning, possibly because they are surprised by its reactivity. However, as time passes they become used to it, they probably do not “see” the system anymore but they concentrate on the learning task. Another explanation might be that during the first two lessons students received many metacognitive scaffolds which were reduced during the later lessons. The fact that students received less scaffolds over time could also explain their shift in perception.

Overall, the findings indicated that dynamic scaffolding of self-regulated learning can be supported based on our conceptual model making use of an attention management system. Dynamic scaffolding positively contributed to dyads' performance on the learning task. Analysis of the log files did, however, indicate that the AtgentSchool system had a limited capability to provide cognitive scaffolds without the help-questions of learners. The system seemed especially effective for metacognitive scaffolds following the cyclical model of Zimmerman (2002). For this reason our second experimental study focused on the effects of metacognitive scaffolds.

Part II. The effects of metacognitive scaffolding and different forms of scaffolds

In this section the results of the second study focusing on the effects of metacognitive scaffolding and different forms of scaffolds were discussed. This study was different from the first in a number of ways. First, it only focused on metacognitive scaffolds, whereas in the first study cognitive scaffolds were also used. Second, this study had an elaborate design, measuring students’ activities during learning, group performance, and individual students’ domain and metacognitive knowledge. Third, instead of dyads we used triads, because in a pre-pilot we found that students in triads verbalized their learning activities more than students in dyads. Fourth, we only provided the triads with scaffolds during the first two lessons (2 hours), in the remaining four lessons (4 hours) students worked without support. Finally, we used two different forms of scaffolds, namely structuring and problematizing scaffolds. Structuring scaffolds supported the groups by providing guidelines and examples to support the groups’ metacognitive activities (i.e. providing the students with an example of a plan for the assignment), whereas problematizing scaffolds elicited metacognitive activities from the group (i.e. asking students to make their own plan for the assignment).
Chapter four focused on the effects of metacognitive scaffolding on learning. The research question was: What is the effect of metacognitive scaffolding and different forms of scaffolds on students’ learning? A control group (n=48) was compared to an experimental scaffolding group (n=106). Half of the triads received structuring scaffolds (n=51) and the other half received problematizing scaffolds (n=57). The triads worked on a similar assignment as in the first study for six lessons (6 hours) plus 1 hour pre-test and 1 hour post-test. The goal was to understand the effects of scaffolding on the triads’ learning performance (quality of the paper), individual students’ domain knowledge (knowledge test), the transfer of domain knowledge (application test) and metacognitive knowledge (open questions). The results showed, in contrast with our previous study, that metacognitive scaffolding had no significant effect on group performance. Nevertheless, the trend was in the expected direction. There also was no effect on the domain knowledge students acquired. The absence of effects of metacognitive scaffolding on the students’ domain knowledge was in line with our previous study and as stated above with other scaffolding studies (Bannert, 2006; Bannert et al., 2009; Lin & Lehman, 1999). We did find a significant effect of dynamic scaffolding on students’ metacognitive knowledge, which was in line with other research (Veenman, Blote & Kok, 2005).

With respect to the form of scaffolds, there was a significant medium effect of the form of scaffolds on group performance, the transfer of domain knowledge and on metacognitive knowledge. These findings indicate that problematizing scaffolds were more effective for learning than structuring scaffolds. Bannert (2006) stated that even though metacognitive scaffolding does not affect the quantity of domain knowledge, it does enhance the quality of domain knowledge. This was confirmed for problematizing scaffolds that led to higher transfer of knowledge than structuring scaffolds in our study.

We expected these results to be explained by the fact that problematizing scaffolds stimulated more metacognitive activities than structuring scaffolds. Furthermore, we wanted to examine two widely held assumptions, namely that scaffolds stimulate the students’ activities that they are directed at and lead to lasting changes in the students’ behavior (Pea, 2004). In chapter four, we investigated the effects of scaffolding on the groups' metacognitive activities during and after scaffolding. The sub-question addressed was: Does scaffolding and different forms of scaffolds stimulate metacognitive activities and develop metacognitive skills in small groups? We expected to explain the differential effects of problematizing and structuring scaffolds on learning with quantitative differences in metacognitive activities. We analyzed the learning activities of the 18 triads (n=54) with discourse analysis (6 triads from each condition). In total 108 hours of discourse and 51,339 turns were analyzed. We examined the stimulation hypothesis looking at the triads’ metacognitive activities during the 2 lessons that students received scaffolds and the developmental hypothesis during lessons 3 to 6 after the scaffolding had stopped.
We found that metacognitive scaffolding had a significant positive effect on the quantity of metacognitive activities performed by the triads. These findings confirmed the *stimulation hypothesis*: scaffolding supported triads to engage in more metacognitive activities. We also found that metacognitive scaffolding had a significant positive effect on the quantity of metacognitive activities performed by the triads after scaffolding stopped. This confirmed the *development hypothesis*: scaffolding did indeed continue to have a lasting effect on the triads' metacognitive activities after scaffolding stopped. This was important as scaffolding studies often refrain from creating lasting changes in behavior even within the same setting (Pea, 2004).

With respect to the effect of different forms of scaffolds, we predicted that problematizing scaffolds would elicit more metacognitive activities than structuring scaffolds. This expectation was based on the fact that problematizing scaffolds elicit students’ metacognitive activities and could consequently have a greater effect on the interaction between the group members. Contrary to our expectation, we did not find that problematizing scaffolds stimulated more metacognitive activities than structuring scaffolds, nor did we find that they stimulated more metacognitive activities after scaffolding ceased. Again the trend was in the expected direction, but the differential effect on learning could not be explained by the quantity of groups’ metacognitive activities.

These results demand an explanation: why do problematizing scaffolds yield better group performance, transfer of domain knowledge and more metacognitive knowledge than structuring scaffolds, even though they do not stimulate significantly more metacognitive activities? We cannot answer this question before we know the exact relationship between scaffolding and different forms of scaffolds, metacognitive activities and students’ learning. We assumed that students learn from scaffolding through activities that scaffolds stimulate, but this has not been properly tested. Moreover, there could be qualitative differences in the metacognitive activities stimulated by different scaffolds. In chapter six, we addressed these issues with an additional discourse analysis, looking at the groups' responses to the scaffolds and a statistical analysis combining the learning outcome data from chapter four with the data on metacognitive activities from chapter five. The main question to be answered was: To what extent do metacognitive activities mediate the effects of metacognitive scaffolding and different scaffolds (structuring vs. problematizing) on students’ domain and metacognitive knowledge?

The discourse analysis suggested that structuring scaffolds encouraged students to discuss the application of the example while problematizing scaffolds stimulated them to construct metacognitive activities in interaction with their group members. Hence, structuring scaffolds might foster active metacognitive activities from the students, whereas problematizing scaffolds might trigger more constructive activities embedded in intensive interaction. Constructive activities are likely to be more effective than active activities at aiding knowledge acquisition (Chi, 2009). Thus, this qualitative difference in the student interactions might help explain why problematizing scaffolds were associated
Discussion and Conclusion

with greater learning, while structuring scaffolds were not. This is an important finding, because it suggests that the effect of metacognitive scaffolds on learning operates through both a greater number of metacognitive activities within the group and the individual students' involvement in the metacognitive activities.

The statistical analysis assessed the relationship between scaffolding and different forms of scaffolds, the individual students' own and the other group members’ metacognitive activities and students’ domain and metacognitive knowledge, while controlling for other learning activities (cognitive, relational and off-task activities). The results of this analysis confirmed previously reported results that students receiving either form of metacognitive scaffolds (structuring or problematizing) displayed more metacognitive activities, and that students receiving metacognitive scaffolds had more metacognitive knowledge than students who did not receive any scaffolding. Furthermore, we found that metacognitive activities mediated the effects of the scaffolding on students’ metacognitive knowledge. However, only individual students’ own metacognitive activities significantly influenced their metacognitive knowledge. Additionally, students performing proportionately more cognitive activities and proportionately fewer off-task activities scored higher on the metacognitive knowledge test.

With respect to domain knowledge, this analysis showed that students in the problematizing condition did have more domain knowledge than those in the structuring and control condition. The difference in results compared to chapter four was probably due to a different sample: due to the labor intensive nature of the research we could only use the subsample of 18 triads for which we coded the learning activities. Again the individual students' own metacognitive activities mediated the effects of the problematizing scaffolds on their domain knowledge. Additionally, students performing proportionately more cognitive activities scored higher on the domain knowledge test. Furthermore, when a student’s group mates performed proportionately more relational activities, that student scored higher on the domain knowledge test. Contrary to our previous suggestion and Bannerts' statement (2009) that metacognitive scaffolding does not influence the quantity of domain knowledge, this seems to indicate that when scaffolding influences metacognitive activities in a certain way, it does increase domain knowledge.

These findings indicate that the effects of scaffolding on students’ knowledge were indeed mediated by the metacognitive activities the scaffolds stimulated. Moreover, the discourse analysis indicated that problematizing scaffolds stimulated stronger student involvement embedded in more intensive interaction. This conclusion needs to be treated with caution, because the discourse analysis only looked at the responses of the triads to the scaffolds and did not determine whether these qualitative difference in metacognitive activities continued throughout the assignment. Additionally, even though interaction is likely to enhance the quality of the groups’ metacognitive activities, up until now there is little empirical evidence that confirms this proposition. In part III, we elaborate on these issues.
Part III. Social metacognition, interaction and scaffolding

Until now there has been very little knowledge about metacognitive activities during collaborative learning (Dillenbourgh, Jarvala & Fischer, 2009). It has been proposed that different forms of metacognitive activities occur at various points along the social spectrum in groups, namely individual, other and social metacognitive activities (Iskala, Vauras & Lehtinen, 2004, Iiskala et al., 2011; Hadwin & Oshige, 2011). Moreover researchers differentiate between different types of interaction in which cognitive activities are embedded (Chi, 2009; Webb, 2009; Weinberger & Fischer, 2006). Cognitive activities embedded in more transactive interaction have been found to influence students’ learning more (Weinberger & Fischer, 2006). So far this distinction has not been applied to metacognitive activities during collaborative learning. In chapter seven, therefore, we focused on the question: How are metacognitive activities embedded in interaction during collaborative learning? To examine this issue, we selected the collaborative discourse from six control groups (n=18) from the second study, who engaged in 996 metacognitive episodes.

The majority of metacognitive activities were social metacognitive activities, but there was a small proportion of individual and other metacognitive activities in the groups’ interactions. This analysis indicated that the groups’ social metacognitive activities were indeed embedded in different types of interaction. We found ignored, accepted, shared and co-constructed metacognitive activities in our sample. Most metacognitive activities were shared, as they were embedded in episodes in which the group members related to each other’s metacognitive contributions with new metacognitive remarks. There was also a substantial amount of accepted metacognitive activities that were immediately engaged in by the group members’ cognitive activities. There were quite a number of ignored metacognitive activities that were not taken up by the group members at all. Finally, we only found a small number of co-constructed metacognitive activities.

As expected we found that metacognitive activities in more transactive interaction were more likely to facilitate the group process. This confirms that interaction in which group members relate to and engage in each other’s contributions adds to the quality of metacognitive activities. This verifies that findings from collaborative learning research (Chi, 2009; Webb, 2009; Weinberger & Fischer, 2006) are also applicable to metacognitive activities. Moreover, shared attention among the group members at the start of a metacognitive episode supported transactive interaction. Overall these findings indicate that for the analysis of metacognitive activities in small groups, it is important to take into account the type of interaction these activities are embedded in.

Finally, we wanted to take a close look at how scaffolding during collaborative learning influenced the way metacognitive activities were embedded in the interaction among the students. We also wanted to confirm our previous proposition about qualitative differences between metacognitive activities stimulated by different scaffolds. In chapter
Discussion and Conclusion

eight, we addressed the sub-question: What is the effect of metacognitive scaffolding on the way metacognitive activities are embedded in interaction? We examined the effect of scaffolding and different scaffolds on the relative frequency of the different types of metacognitive activities embedded in the interaction of 18 triads (n=54) from study 2. We tested the transactivity hypothesis that states that scaffolding increases transactive interaction and the shared attention hypothesis that proposes that scaffolding stimulates shared attention among group members.

We found that students receiving scaffolding showed significantly more co-constructed metacognitive activities than groups that did not receive scaffolding. This indicates that scaffolding positively influenced students' uptake of metacognitive activities. This is in line with earlier findings (Barron, 2000; 2003) that indicate that the difference between successful and unsuccessful groups in problem-solving is not caused by the quantity of possible solutions, but by the uptake of those solutions by the group. Moreover, groups receiving problematizing scaffolds showed significantly fewer ignored metacognitive activities and more co-constructed metacognitive activities than groups receiving structuring scaffolds. These findings suggest that scaffolding had a differentiating effect on the groups' interaction and different forms of scaffolding seemed to influence the groups’ interaction differently. Scaffolding was not found to have an effect on the students’ shared attention. These findings indicate that under the right circumstances scaffolding can support collaborative learning. Thus the relation between scaffolding and collaboration needs further research, but it could be a promising combination to enhance students' metacognitive knowledge and skills for future learning in complex computer-based environments.

Developing metacognitive knowledge with scaffolding during collaborative learning

Answering our main research question – What are the effects of computerized scaffolding of self-regulated learning on the learning of collaborating students? – we established that computerized scaffolding of self-regulated learning has a small to medium positive effect on group performance and also positively influenced the groups’ perception of their collaboration, their teacher, their initial opinion of the software and the agent. Metacognitive scaffolding also showed a similar small to medium effect on group performance but this was not significant. We did not find an effect of scaffolding on domain knowledge. We did find that metacognitive scaffolding had a small positive effect on students’ metacognitive knowledge. Finally, looking at the groups’ activities during learning, we found that metacognitive scaffolding had a medium to large positive effect on the groups’ metacognitive activities and a large positive effect on co-constructive metacognitive activities. Thus our scaffolding systems stimulated groups’ metacognitive activities, enhanced the way metacognitive activities were embedded in interaction and consequently improved students’ metacognitive knowledge.

Reflecting on the goal of our computerized program, namely to support small groups in complex computer-based learning environments to enhance the regulation of
their learning, the findings suggest that we succeeded in stimulating students’ metacognitive activities and knowledge. Although this seemed to support group performance, we did not find an effect on domain knowledge. It is important to note that the assignment was not directly focused on acquiring domain knowledge and that all students in both studies showed more domain knowledge on the post-test. In the light of the results, it is important for practical purposes to determine whether there were any lasting changes of scaffolding on the groups’ metacognitive activities. We established that groups receiving scaffolds continued to apply more metacognitive activities after the scaffolding stopped. Moreover, we found that problematizing scaffolds outperformed structuring scaffolds on a number of issues. Problematizing scaffolds resulted in better group performance, more transfer of domain knowledge and more metacognitive knowledge. These differential effects on learning could not be explained by quantitative differences in metacognitive activities. We did find students in the problematizing condition showed fewer ignored metacognitive activities and more co-constructed metacognitive activities than those in the structuring condition. The combination of quantitative and qualitative differences seems likely to explain the differential learning effects of problematizing scaffolds.

Our studies increased our understanding of how scaffolding in collaborative settings influences learning. First, small groups receiving metacognitive scaffolds showed more metacognitive activities and continued to show more metacognitive activities after scaffolding stopped. Second, the effect of scaffolding on students’ knowledge was mediated by the metacognitive activities. Third, students’ own activities influenced their learning significantly, whereas other students’ activities had less impact. Fourth, qualitative differences in the way activities were embedded in interaction (more or less transactive) seemed to influence the students’ learning from scaffolding. Finally, different forms of scaffolds can have differential effects on students’ transactive interaction. These findings indicate that scaffolding in small groups was strengthened by the interaction among the group members. This means that scaffolds could be designed in ways that are more attuned toward eliciting students’ interaction. Future research needs to test the proposition further but if it were to be confirmed, scaffolding during collaborative learning could be a powerful mechanism to enhance students’ metacognitive knowledge and skills.

Limitations

As in all research, there are a number of limitations to take into account. This study was very specific with respect to its sample, the context and the learning task, and therefore generalization of the results should be carefully considered. The sample in our studies consisted of young learners in elementary education aged 8-12. Young learners are likely to have less developed metacognitive knowledge and skills than older learners, and so studies with learners from different age groups would be needed to validate the results for other groups. The context in our studies was a computer-based e-learning environment with mostly text and pictures. Future research would need to determine whether this...
scaffolding system could also facilitate learning in other computer-based learning environments, for instance games, immersive environments or mobile learning environments. Moreover, the assignment was a research task in the geography domain with a writing assignment. Future work should assess whether a task with a stronger focus on domain knowledge and in different domains could also be supported in this way. Furthermore, the sample size of measurements at the group level was restricted. In the process analysis the sample size was even smaller, though this was partially compensated by the large volume of analyzed coded utterances (51,399). This limited the power of our analysis and non-significant results should be treated with caution.

With respect to the measurement of metacognitive knowledge, we used a self-designed context-specific metacognitive knowledge questionnaire. This questionnaire correlated with the measurement of metacognitive activities performed by the students, which indicates that it solved some of the issues around the measurement of metacognitive knowledge (Veenman, 2011). However, this questionnaire was not suitable for a pre-test. We were therefore unable to measure the students' existing metacognitive knowledge, which makes it impossible to say anything about the students’ development or the differential effects of initial metacognitive knowledge. Another limitation is that we measured the groups’ metacognitive activities after scaffolding within the same setting and context. This allows us to conclude that, within the same task and context, scaffolding did lead to lasting changes in behavior, we do not know whether these effects will be confirmed in other assignments in another learning environment, group or learning domain. Moreover, it can be argued that some metacognitive activities are not explicit, but implicit in the occurrence of higher cognition (Veenman et al., 2006). For these reasons the measurement of metacognitive activities was not exhaustive for all metacognitive activities occurring within the triads. Future research needs to address the transfer issue and find a solution to adequately pre-test metacognitive knowledge.

Finally, we raise the question of how dynamic our scaffolding system really is. The development of computerized scaffolding systems is driven by the positive effects of scaffolding with human tutors and the infeasibility of personalized scaffolding in schools. Other examples of such recently developed systems are MetaTutor for college students learning in hypermedia (Azvedo et al., 2010a,b, in press) and Betty’s Brain for middle school children learning science topics (Biswas, Jeong, Kinnebrew, Sulcer & Roscoe, 2010). These systems successfully foster students’ self-regulation and facilitate learning doing this. Inspired by human tutors who determine their scaffolding based on the diagnosis of students’ behavior and reduce it when the students’ competences increase (Wood, Bruner & Ross, 1976; Scharma & Hannafin, 2007), computerized scaffolding systems track and trace students’ activities to diagnose current behavior and select scaffolds that adjust to each student's progress (Azvedo et al., 2010a; Molenaar & Roda, 2008). However, the system’s awareness and interpretation of the students' behavior is still restricted to making localized decisions for scaffolding and feedback, depending on time thresholds for various system- and learner-initiated behaviors. This means that the
scaffolding is dynamically adjusting itself to the students' progress, but it does not fully adapt to their development.

Adaptive metacognitive scaffolding demands the measurement of students’ metacognitive activities during learning. Metacognitive activities are identified based on their manifestation during learning with concurrent thinking-aloud protocols (Azevedo, et al., 2008; 2010a; van der Stel & Veenman, 2010). These measurements are very labor intensive, not concurrent with learning, nor applicable for computer systems. Consequently there is an active debate about new approaches to measure metacognitive activities during learning (Greene & Azevedo, 2010). Multiple data-stream analysis can be used to establish indicators of metacognitive activities using analyzed think-aloud protocols together with data-streams that are measured during learning, for example computer log files, eye tracking, psychological or sensor data. For example, scrolling in the computer log file is found to be an indicator of monitoring (Veenman, Wilhelm & Beishuizen, 2004). Finding valid and reliable indicators of metacognitive activities during learning should therefore be pursued both for system development and to advance research about metacognition and its development.

Apart from measuring metacognitive activities during learning, we suggested in chapter two that the current input into our system was too limited to support the diagnosis of both the cognitive and motivational processes of students. Registering more and different information from the students' environment would allow us to accumulate a better representation of the individual learner’s attentional focus. This could enhance our ability to position interventions in relation to cognitive and motivational processes. For example, the effectiveness of cognitive scaffolds could be enhanced using eye tracking, which would provide a better diagnosis of the learner’s current focus and related cognitive activities. The use of a webcam to assess the emotional state of a student could provide better input to the system to support the diagnosis of the learner’s motivation and provide scaffolds supporting this.

**Future research directions**

In this thesis, we elaborated extensively on the effects of scaffolding on students' activities and learning. However, we have still not analyzed all of the data-sets we collected. For example, students’ epistemological beliefs about the nature and sources of learning could interplay with their willingness to engage in learning in open complex computer-based learning environments. This could also affect their response to scaffolding and their willingness to engage in active construction of their own metacognitive activities. Moreover, the data-sets we did analyze could benefit from further analysis. Our process analyses looking at students' metacognitive activities were on a holistic level (Reimann, 2009). Holistic analyses consider the process as one unit without aiming to understand the temporal or sequential aspects within the process (Azevedo et al.,2010; Reimann, 2009;
Wampold, 1992). Attention for temporal aspects could help us understand how scaffolding influences the positioning of metacognitive activities over time. For instance, does scaffolding support more planning at the beginning of a task? Concentration on sequential aspects could support more insights into the effect of scaffolding on the pattern of the learning activities. For example, does scaffolding affect the position of the metacognitive activities in relation to cognitive activities? Thus process analysis looking at the temporal and sequential effects of scaffolding could produce further evidence in support of our understanding of how scaffolding influences learning in collaborative settings.

Taking a broader perspective, the results of our research provide a number of suggestions for new research. Our research showed that metacognitive activities are important for regulating group learning in Computer-Based Learning Environments (CBLEs). Students who orientate, plan, monitor and evaluate perform better than students who do not engage in these metacognitive activities as shown in this thesis and by others (Azevedo, Cromley, Winters, Moos & Greene, 2008; Bannert, Hildebrand & Mengelkamp, 2008). We showed that scaffolding can support the development of metacognitive knowledge. Moreover, other research indicates that metacognitive skills (i.e. the ability to apply metacognitive activities to regulate one’s learning) are a significant predictor of students’ learning performance, possibly even more important than intelligence (van der Stel & Veenman, 2010). Although the importance of metacognitive knowledge and skills is recognized and there is abundant research evidence showing that students do not regulate their learning in CBLEs sufficiently, little attention has been given to how to develop students’ metacognitive knowledge and skills to foster learning in these complex environments (Azevedo et al., 2008). Until now, most research has concentrated on scaffolding to stimulate regulation to enhance domain knowledge acquisition (Azevedo, et al., 2008; Land & Greene, 2000).

We know very little about the development of metacognitive skills and knowledge of young students in elementary education. This is partly due to difficulties measuring metacognitive activities and to the belief that the development of metacognitive knowledge starts when students are older (Azevedo 2010; Schraw, 2010; Veenman, 2011). We found that computerized scaffolding supported the development of metacognitive knowledge by stimulating students’ metacognitive activities. Interaction among peers also seemed to support the development of young students’ metacognitive knowledge. Moreover, initial stimulation of the scaffolds seemed to be taken over by the group. Further research is therefore needed to examine under what conditions scaffolding during collaborative learning could support the development of students’ metacognitive knowledge and skills.

Future directions for development of scaffolding systems

In the limitation section, we emphasized the need to measure metacognitive activities concurrently during learning to enhance our scaffolding system. There have been some interesting findings for scaffolding with a 3D virtual agent as used in our system. Research has established the so-called mere belief effect, which demonstrates that the
belief one is having of social interaction (believing that you are interacting with a human) leads to higher arousal, attention, and learning (Okita, Bailerson & Schwartz, submitted). Additionally the protégé effect asserts that even though young learners know the embodied agent is not real, they still show strong social responses that improve learning when working with these agents (Chase, Ching, Opperzo & Schwartz, in press). Hence, the communication and presentation of the scaffolds to the learner seems to be an important issue. The effects of the usage of modalities are largely unknown; for example, one can use modalities such as text messages, agents or even robots. With respect to the embodied agent, we know very little with respect to the usage of its emotions, appearance, animations and their effects on fostering student activities and learning. This emphasizes the need for further research into modality effects and the usages of the embodied agent.