Communication Patterns and Their Role for Conceptual Knowledge Acquisition From Productive Failure

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Abstract: In *Productive Failure* (PF), students struggle with a problem in small groups before receiving instruction on the correct solution, which has been shown to enhance conceptual knowledge acquisition. Explanations for the effectiveness of PF point at the importance of contrasting the student's solution ideas with critical aspects of the correct solution during instruction. However, other mechanisms of PF have not yet been investigated in detail. Here, we focus on the role of communication patterns during the initial problem-solving phase. Using existing process data from a PF study, we investigated communication patterns based on the ICAP-model and correlated them with prior knowledge, quantity and quality of student solutions, and conceptual knowledge at post-test. Our findings suggest that interactive communication during the initial problem-solving phase only fosters conceptual knowledge if students discuss those ideas that particularly lend themselves to being contrasted with critical aspects of the correct solution during the subsequent instruction phase.

Introduction

Imagine a learning situation where a small group of students has to deal with a mathematical problem to an unfamiliar concept (e.g., variance). Presenting students the canonical (i.e., correct) solution of a specific mathematical problem first and letting them practice afterwards is a common approach to teaching students mathematical concepts. From a constructivist point of view, this instructional design may neglect the potential of students using their prior knowledge and intuitive ideas for fostering a more elaborate understanding of the learning material (cf. Moshman, 1982).

An alternative instructional design for teaching mathematical concepts that goes along with constructivist principles is *Productive Failure* (PF). The central design principle of PF is to ask students to solve a domain-specific problem prior to receiving instruction on that concept (Kapur, 2014). Research on PF suggests that successful conceptual knowledge acquisition is strongly intertwined with the possibility of struggling with a problem before learning how to solve the problem correctly. Struggling with an – at the time of problem solving – unfamiliar problem helps students to activate their prior knowledge and to explore the problem-solving space by generating and contrasting different solutions (Kapur, 2014).

During the problem-solving phase of PF, the students typically generate a certain number of solutions, which are more or less useful for solving the given problem. Because the given problem is based on new learning objectives, the students generally fail to find the correct solution. However, when students try to solve a problem by generating their own ideas, they activate prior knowledge and intuition to create solutions (Kapur, 2014), which can be contrasted to the canonical solution during subsequent instruction. "*One explanation of the better performance of PF students comes by way of prior knowledge activation and differentiation during the problem-solving phase, which may help them better notice and attend to critical features of the concept*" (Kapur, 2014, p. 1018). In other words, struggling with a complex problem before getting the correct solution can 1) activate prior knowledge and intuitive ideas and 2) help students to understand the canonical solution afterwards because they already noticed the limitations of their ideas during problem solving. This awareness can be useful to get a deeper understanding of the topic because students are likely to focus on the relevant aspects of the problem during the instructional phase.

This awareness can also prepare the students for the conceptual knowledge acquisition that happens during the instruction phase even if they were not able to solve the problem correctly (Kapur & Bielaczyc 2012; Loibl & Rummel, 2014). Research has shown consistently that PF promotes conceptual understanding more than presenting students the correct solution of a problem first (e.g., direct instruction) followed by solving practice problems afterwards (Kapur, 2014, Kapur & Bielaczyc 2012; Kapur & Kinzer, 2009; Loibl & Rummel, 2014). So far, research of PF has identified necessary conditions for the instruction phase to be effective. Loibl and Rummel (2014) showed that student ideas that contrast with the canonical solution presented during instruction might be relevant for the effectiveness of PF. Yet it is still unclear what processes during the initial problem-solving phase prepare students best for the following instruction. The fact that the problem-solving phase is usually implemented in small group collaboration may play an important role here. Different patterns of communication (i.e., discussions) may be more or less suited to foster the possibilities of contrasting different solutions.

Nearly all studies of PF implemented the initial problem-solving phase in small groups (Kapur, 2014; 2014; Loibl & Rummel, 2014). During small group collaboration, students perform activities such as discussing, explaining, or listening to explanations. Ample research (including several meta-analyses) has shown that collaboration has positive effects on conceptual knowledge acquisition (Johnson & Johnson, 2002, 2009; van Boxtel, van der Linden, & Kanselaar, 2000). With regard to PF, Sears (2006) found that students showed more knowledge-sharing behavior when having to solve unfamiliar problems in comparison to students who first received instruction and solved familiar problems afterwards. Thus, struggling with an unfamiliar problem seems to go along with (or require) specific communicative patterns. A quasi-experimental study by Mazziotti, Loibl and Rummel (2015) investigated the impact of collaboration on the effects of PF. However, they did not find differences between an individual and a collaborative PF condition. A reason for their finding could be that the students did not collaborate effectively (Mazziotti et al., 2015). More generally, it is likely that communication can enhance the effectiveness of PF only under certain conditions. Therefore, it is interesting to look closely at communication patterns taking place in a PF setting and to investigate how they affect the effectiveness of PF. Moreover, the importance of the student constructed ideas generated during the problem-solving process have not been investigated. There is a need to investigate two aspects of learning from PF: 1) How relevant are specific communication patterns during problem solving for knowledge acquisition? 2) About what intuitive ideas students have to communicate during problem solving?

In this paper, we are presenting process analyses of data from a typical PF setting. By analyzing different communication patterns during a problem-solving phase, our findings provide the first evidence for answering the questions above. We analyzed the process data of a collaborative problem-solving phase from a PF study (Loibl & Rummel, 2014) by building upon the ICAP-Model by Chi and Wylie (2014) to identify different communication patterns (e.g., passive observation or interactive communication) and evaluated their relation to students' conceptual knowledge acquisition in a PF setting. With this analysis, we want to provide a basis for experimentally testing hypotheses concerning the relationship between collaboration (specifically, communication patterns) and learning in PF. In the following paper, we deal with these issues by building upon the ICAP-Model as a central framework for our analysis.

The ICAP-Model by Chi and Wylie (2014) is a framework that characterizes central learning activities that can emerge during learning situations. The acronym 'ICAP' (**I**nteractive-**C**onstructive-**A**ctive-**P**assive) describes these learning activities. The activities are listed in descending order with reference to their attributed potential to foster learning outcomes. Chi and Wylie (2014) argue that interactive learning activities are most effective and passive activities are the least. It is important to stress that – with the exception of interactive activities (defined as strongly intertwined contributions of at least two individuals) – the described learning activities do not solely focus on social learning situations. Nevertheless, the mentioned learning activities are useful to characterize communication patterns during problem solving in small groups (cf. Deiglmayr, Rummel, & Loibl, 2015). For instance, Chi and Wylie (2014) describe passive activities as the 'passive' perception or observation of information (e.g., watching a video or reading a text). Such an activity can also be performed during communicative learning situations (e.g., listening to an explanation). Active learning activities are defined as 'actively' manipulating or dealing with the learning environment (e.g., coordinating by highlighting an important object) and constructive activities as generating new information by elaborating on prior knowledge (e.g., explaining, arguing for new ideas). In a collaboration setting, students can engage in monologues that fit these definitions. Thus, we argue that ICAP is a manageable way to categorize communication patterns during collaborative problem solving.

Interactive learning activities describe learning situations where at least two individuals co-construct ideas (e.g., discussions). If a large extent of the communication processes within small groups are interactive, this implies that individuals are dealing with each others' ideas during the communication process (cf. Stahl, 2013; Teasley, 1997). In other words, communicative actions are interactive when ideas or thoughts of more than one individual are strongly intertwined. One important criterion of strong (i.e., interactive) collaboration is synchronous communication (Dillenbourg, 1999). Along with most theoretical approaches on collaborative learning (Dillenbourg, 1999; Stahl, 2013), the ICAP-Model points out that interactive activities outperform non-interactive activities concerning conceptual knowledge acquisition (Chi & Wylie, 2014). Therefore, in particular, interactive communication may have the potential to prepare students for conceptual knowledge acquisition during instruction.

During the problem-solving phase of PF, learners struggle with each others' ideas to deal with an unknown problem. Mugny and Doise (1978) argue that struggling with different points of view during strongly-interactive learning situations can lead to socio-cognitive conflict, especially when students have to bring together diverging aspects or ideas. With reference to Piaget (1977), a socio-cognitive conflict describes a situation where learners try to assimilate their ideas to the ideas of other learners (see Piaget, 1977; Mugny & Doise, 1978). In the case that assimilation fails, students may realize that there is a need for accommodation in their existing concepts because their ideas do not fit to other ideas or are not useful for solving the given problem. Therefore, interactive communication during problem solving may foster knowledge acquisition from PF because socio-cognitive conflicts are a good preparation for the following instruction.

The theory of socio-cognitive conflicts could explain why PF is potentially more productive when students have the chance to interact with each other. When students are communicating interactively, they may 1) bring in intuitive ideas, 2) contrast them during conflicts, and 3) discuss possible differences, which may lead to the co-construction of new ideas to solve the given problem. From that point of view, interactive communication can increase the effectiveness of PF. With reference to Chi and Wylie (2014), we assume that interactive sequences during problem solving outperform passive, active, and constructive communication processes concerning conceptual knowledge acquisition.

Building upon this work, we analyzed process data from the study by Loibl and Rummel (2014), which will be explained in more detail below. More specifically, the focus of our analyses was to carve out which communication patterns during problem solving prepare students the best for the instruction afterwards. For instance, it could be better for knowledge acquisition if students were communicating actively (e.g., by giving explanations) or interactively (e.g., by discussing with each other) rather than just observing communication processes (e.g., by listening to their partner's explanations). To analyze the video material, we used the following communication pattern categories: 1) passive observation, 2) active-constructive, and 3) interactive communication. In our data, active and constructive activities could not be meaningfully separated. We therefore combined these activities into one category. Because communication patterns are probably not the only important preconditions for effective knowledge acquisition from PF, we also took into account the quantity and quality of students' solutions, and their prior knowledge. By analyzing communication patterns together with these measures, we are able to investigate under which conditions the problem-solving phase prepares students most effectively for the following instruction.

Study by Loibl and Rummel (2014)

The process analyses presented here are based on data collected by Loibl and Rummel (2014). Therefore, we will first briefly describe the methods from this study before we explain in more detail our analyses. Loibl and Rummel (2014) compared the *timing of instruction* (i.e., before or after problem solving) and the *form of instruction* (i.e., with or without contrasting student solutions to the canonical solution) in a quasi-experimental 2x2 design with pre- and posttest measures. Participants were 10^{th} graders from secondary schools in Germany. For our analysis, we used one condition of the study. In this condition, students first worked on a mathematical problem in small groups. After struggling with that problem, the students were introduced to the canonical solution through direct instruction. During the instruction phase, student solutions were contrasted with the canonical solution. The length of the two phases was inspired by a typical teaching unit in Germany, and therefore took 45 minutes for each phase. We analyzed 14 groups, consisting of three students each for a total of N = 42 students. The average age was M = 15.85 (SD = .66). The mathematical problem students received was about the concepts of variance with the two formulas: *mean absolute deviation* (MAD = $\sum|x_i$ - mean$|/N$) and *standard deviation* [SD = $\sqrt{}(\sum(x_i$ - mean$)^2/N)$]. The problem was adopted from Kapur (2012). Students had not received instruction on variance in school prior to the study. In the following sections, we describe variables used by Loibl and Rummel (2014), which we took into account for our analysis: 1) prior knowledge, 2) quantity and quality of student solutions, and 3) conceptual knowledge at post-test. We then describe the new process analysis (communication patterns) of our analysis.

Pretest

A pretest measured students' knowledge about descriptive statistics and graphical representation (as a prerequisite for learning the concept of variance) and asked students to report their final grades in mathematics of the last two school periods. In Germany, '1' represents the best grade while '6' represents the worst grade. To facilitate interpretation, grades were reverse-coded so that '1' represents the worst grade and '6' the best grade.

Quantity and quality of student solutions

The quantity and quality of student solutions refer to the knowledge co-construction during the problem-solving phase implemented by Loibl and Rummel (2014). As described above, the problem students received was related to the MAD and SD formulas. Both formulas have the following components: 1) sum up deviations for all data points to obtain a precise result, 2) take absolute or squared deviations (i.e., positive values) to prevent positive and negative deviations from canceling each other out, 3) take deviations form a fixed reference point (the mean) to avoid sequence effects, and 4) divide by the number of data points to account for sample size. For the process analyses, the number of components included in each student solution was counted. Component 4 (division by the number of data points) was excluded from this paper, because for the analyzed condition, there was nearly no communication concerning that component, and the given problem did not require the division by the number of data points (see component 4 above) to solve the problem correctly. For all of the solutions, we assigned them to a category (C0-C3). Solutions that do not include any of the above components were classified as category 0. Solutions with one correct component were categorized as category 1 and so on. Therefore, solutions of a lower category are 'more incorrect', because they disregard more components. Notably, the categories focus on the number of correct components within one solution and do not indicate which of the components are included. In addition, an overall indicator of quality for the student solutions, which we refer to as *total quality*, was formed by determining the maximum number of components included across all solutions. The quantity of student solutions was measured by counting different solutions, notwithstanding how useful they were to solve the given problem.

Posttest

Conceptual knowledge was tested by four posttest items. Items included an explanation for a graphical solution, the identification and explanation of presented mistakes, and the correct assignment of graphical representations. The maximum score on the test for all four items was seven points.

Analysis of communicative patterns during problem solving

In order to investigate the relevance of small group collaboration for the effectiveness of PF, we performed a process analysis of the PF-condition in which students first engaged in problem solving and afterwards received instruction building on student solutions, implemented by Loibl and Rummel (2014). For the analysis, we used video data of the initial problem-solving phase. As described above, each video of the group problem-solving process had a length of 45 minutes.

Building upon the ICAP-Modell by Chi and Wiley (2014) we differentiated between three communication patterns: 1) passive observation, 2) active-constructive communication, and 3) interactive communication. As mentioned above, these communication patterns are describing different participative, task-relevant behaviors during the problem-solving phase. We cut the videos (45 minutes each) of the problem-solving phase in 270 10-second sequences. Each sequence was analyzed separately for each student in the groups (see *Table 1* for an example). During each sequence, a student was communicating about task-relevant information concerning the different solutions, which was assigned to a specific category (C0-3). For example, as you can see in *Table 1*, a student's communication status was rated as *interactive* during a given 10-second segment when there was at least one more contribution of another student within the same segment. When there was not, the contribution was classified as *active-constructive*. If a student did not communicate during a 10-second sequence while at least one other groupmate did, we rated the non-communicative behavior of the student as *passive observation*. We only considered task-relevant communication (e.g., explanations, confirmations, discussions, accentuations) and did not analyze the quality of a contribution (e.g., high elaboration). This resulted in three dependent variables: how often a student communicated during problem solving, in what form or pattern communication occurred (passive, active-constructive, interactive), and to what kind of solution-category (C0-3) it was related. These variables were useful to measure, how students communicated during problem solving, as you can see in Table 1.

Table 1: The coding matrix to measure the three communication patterns

Time in sec.	Sequence 1 00:00:00	Sequence 2 00:00:10	…	Sequence 269 00:44:40	Sequence 270 00:44:50
Student A	C 1 Interactive	C 2 Active-constructive	…	-	C 3 Interactive
Student B	C 1 Interactive	- Passive	…	-	- Passive
Student C	C 1 Interactive	- Passive	…	-	C 0 Interactive

To account for differences in verbosity, we computed relative frequencies of each communication pattern for each group member by dividing his or her number of communication patterns by the total number of all communication patterns for the group as a whole. For example, one group had a total of '100' interactive 10-second sequences during problem solving. In this case, student A participated on '80', student B on '30', and student C on '100' 10-second sequences. We divided the values of each student by the total frequency of interactive communication (in this case '100'). If one member of the group communicated in every interactive sequence during problem solving (e.g., student C), the student gets assigned a value of '1', which means, that the student was involved at 100% of the interactive 10-second sequences during the 45 minutes. Using this method, we computed the values for each member for each of the three communication patterns.

Results

The findings we present focus on 1) prior knowledge, 2) quantity and quality of student solutions, and 3) the three communication patterns. We analyzed which of these variables has an impact on conceptual knowledge acquisition. We analyzed the data with *Pearson* correlation coefficient (r). If variables were not normally distributed, we used the non-parametric coefficient *Spearman's Rho* (r_s).

Pre-test scores did not correlate significantly with conceptual knowledge acquisition (r_s = .278, ns), but average mathematics grade did correlate with conceptual knowledge acquisition (described in detail below; r = .365, p < .05). In our process analyses, we therefore used the average grades in mathematics as an indicator for relevant prior knowledge. This grade can be seen as a measure of conceptual knowledge of mathematical contents and also the ability to solve mathematical problems. Prior knowledge also correlated with task-relevant communication (r = .358, p < .01). Students with better grades in mathematics showed less passive observation (r = -.404, p < .01) and participated with more active-constructive communication than their other group members (r = .419, p < .01). However, the correlation between the grade in mathematics and the frequency of interactive communication was only marginally significant (r_s = .285, p = .065).

Concerning the quantity and total quality of the generated solutions within the groups, there were no significant correlations with conceptual knowledge acquisition. Neither the quantity of generated solutions (r_s = -.086, ns) nor the quality (r_s = -.014, ns) within the groups correlated significantly with conceptual knowledge acquisition. Hence, the quantity and also the quality of generated solutions seemed to be of no importance for conceptual knowledge acquisition.

Next, we analyzed the relation between the communication patterns and posttest results. Concerning the three communication patterns, there were no significant findings with respect to knowledge acquisition. Neither for passive observation (r = -.172, ns), active-constructive (r = .149, ns), nor for interactive communication (r_s = .073, ns) was a positive correlation with knowledge acquisition found.

The following analysis of the communication patterns takes into account the quality of individual student solutions, each coded for the number of components included (C0-C3). With respect to the four qualitative categories of student solutions (C0-C3), we analyzed the communication patterns separately. It is notable that only for solutions of category 1 (i.e., solutions including one component) was there a significant correlation between the frequency of active-constructive communication and conceptual knowledge acquisition (r_s = .381, p < .05). This same pattern was found for interactive communication as well (r_s = .424, p < .01). It seems that active-constructive and interactive activities for students along with generated solutions of category 1 are associated with better conceptual knowledge acquisition. Further analyses of variance have shown that this is true particularly for interactive activities, thus we only describe the analysis of variance for interactivity. For the further analyses, we took into account the students' score of active-constructive communication (high or low) and if solutions of category 1 were available during group discourse or not. We did the same for students' interactivity scores. As already mentioned, analyses of variance only showed effects when we took into account interactivity, as we describe it in more detail below. Therefore, higher frequencies of interactive behavior during problem solving only seem to be more or even only effective when groups struggled with solutions of category 1. Remember that solutions, which were assigned to this category, only included one solution component.

In order to support the assumption of an interrelation between more frequent interactive behavior and the availability of solutions assigned to category 1 as described above, we compared the factors *Interactivity* (high / low) and *Solutions of Category 1* (available / not available) within an ANCOVA, using mathematical grade as a covariate and scores on the post-test as the dependent variable. *Interactivity* (high / low) was based on a median-split of frequency of interactive communication patterns (*Md* = .77). In Table 2 you can see the means and standard deviations of the four subsequent conditions that we analyzed.

Table 2: Descriptive statistics which was analyzed within an ANOVA (Interactivity vs. Solutions of Category 1)

Solutions of Category 1	Interactivity	*N*	Conceptual Knowledge Acquisition *M (SD)*
available	high	13	3.50 (1.52)
available	low	13	2.34 (1.46)
not available	high	8	1.56 (.86)
not available	low	8	2.31 (1.09)

As you can see in *Table 2,* students who struggled with solutions of type category 1 and participated with high interactivity during problem solving, outperformed the other conditions with respect to conceptual knowledge acquisition. If students participated with low interactivity during problem solving, it seems to be irrelevant if they struggled with category 1 solutions or not (see *Table 2*). The worst results for conceptual knowledge acquisition were achieved by students who were interactive but did not struggle with category 1 solutions. The main effect of the factor *Solutions of Category 1* (available / not available) was significant, $F(1, 37) = 4.480$, $p = .041$, $\eta^2 = .108$), but the main effect of the factor *Interactivity* (high / low) was not, $F(1, 37) = .064$, $p = .802$, $\eta^2 = .002$). Further, there was a significant interaction effect between the two factors, $F(1, 37) = 5{,}320$, $p = .027$, $\eta^2 = .126$). This interaction particularly suggests that students who participated often in forms of interactive communication achieved better posttest results when they struggled with solutions of category 1. If there was no communication about solutions of category 1, interactive students achieved the lowest conceptual knowledge scores despite being interactive.

Conclusions and implications

Our findings suggest three initial conclusions: 1) favorable prior knowledge goes along with conceptual knowledge acquisition from PF; 2) solutions of category 1 seem to be of high importance for learning, particularly when 3) solutions of that category are linked to student's interactive communication.

First, we want to discuss the positive correlation between prior knowledge and conceptual knowledge acquisition. Our findings are in line with Kapur's (2014) assumption that the activation of prior knowledge during problem solving has an important role for the learning process. At this point it is important to stress that this requires the learner to have enough prior knowledge to work on the unknown problem and to not have too much knowledge to find an adequate solution for the given problem effortlessly. "*So the productive failure method depends strongly on choosing a problem that is inside this window with respect to the students' prior knowledge*" (Collins, 2012, p. 733). This could explain why the math grade, as an indicator for more comprehensive prior knowledge, correlated significantly with conceptual knowledge acquisition, and the specific prior knowledge did not. Maybe it is more important that students are highly skilled in solving mathematical problems than knowing much about the actual problem. Nevertheless, better prior knowledge seems to be an important condition for knowledge acquisition from PF.

Further, our findings suggest that, in particular, working on solutions of category 1 seem to foster conceptual knowledge but only when engaging in interactive communication. To interpret this finding, it is necessary to understand why solutions of category 1 are so fruitful for knowledge acquisition. This can be explained against the background of the final phase of PF, where student solutions are contrasted with each other and the canonical solutions. In contrast to the other categories (C0, C2, and C3), solutions of category 1 can be described as an intermediate step to the canonical solutions. In other words, these solutions are neither too far (as C0) nor too close from the correct solution (as C3 and possibly C2). As we mentioned above, the categories represent the number of components of the canonical solution that were correctly included in the solution attempt. Taking that into account, one can argue that solutions that do not include important solution components cannot be contrasted to the canonical solution during the instruction afterwards because there are no aspects, or too many aspects, to contrast. Further, if a solution includes all (C3) or close to all (C2) solution components, there is less space for contrasting because the differences between the canonical solution and the student solutions are too low. Solutions of category 1 may offer the highest potential for contrasts and differentiation. If this is true, why did solutions of this category only enhance conceptual knowledge acquisition when linked to interactive communication?

It is important to stress that the knowledge acquisition from PF does not take place during the problem-solving phase. Rather the conceptual knowledge acquisition happens afterwards, during direct instruction with contrasting solutions. The problem-solving phase serves as a preparation for the following instruction. In the words of Piaget (1977), students should assimilate intuitive ideas to the problem space to recognize that their solutions or concepts are not completely useful to solve the given problem. If they do so, the student's concepts can be accommodated during the instruction afterwards, but only if the instruction appeals to their concepts or solutions (see Loibl & Rummel, 2014). The point is that students only can recognize that their concepts do not fit as adequate problem solutions when there is an active confrontation during problem solving. For instance, students have to evaluate the solution by reflecting on the process of calculation or the produced result. Like socio-cognitive conflicts introduced by Mugny and Doise (1978), such a confrontation can emerge during interactive communication because students evaluate each other solutions against the background of their own preexisting concepts. This could also explain the interaction effect between interactive communication and the presence of solutions of category 1. When students produced solutions, which are near to the canonical solution (C2 and C3) or too obvious incorrect (C0), they cannot discuss the need or the absence of solution components. In contrast, solutions of category 1 do offer potential for discussion. Therefore, interactive communication may be much more productive or cause conflict when it refers to solutions of this category.

Further, the interactive participation does not only refer to solutions of category 1. A high amount of interactive communication means that the student was participating at the most in interactive sequences during the problem-solving phase. Therefore, high interactive participation of a student refers to almost every solution that was generated by the group. Interactive sequences may prepare for knowledge acquisition afterwards when the student contrasts solutions of category 1 with other solutions of different categories. However, the reason why high interactive communication without solutions of category 1 results in the worst posttest results concerning knowledge acquisition requires further investigation.

The most important limitation of our analysis is the operationalization of the ICAP-Modell (see Chi & Wylie, 2014), because we did not take into account the social learning activities in more detail. For instance, we did not distinguish whether interactive sequences included 'real' discussions (e.g., conflicts, etc.) or just synchronous contributions, which were not linked to each other.

Further, to analyze the presented data, we had to dichotomize the factor *Interactivity* (high / low). Therefore, the classification (high / low; $Md = .77$) was rather data driven rather than based on theoretical assumptions and experimental variation. Further, because of the small sample size (42 students; 14 groups), it was difficult to control for other important factors such as the quantity of solutions or group composition (see Loibl & Rummel, 2014). However, the analysis of various communication patterns during PF gives us the first insights into under which conditions interactive communication during problem solving could foster conceptual knowledge acquisition from PF by preparing students more effectively for the following instruction. Further studies have to take into account that interactive communication can emerge in different forms during problem solving and may exert influence only under certain conditions. One important condition seems to be that interactive communication occurs with those solutions that can be contrasted by the following instruction most effectively. Our findings provide a stepping-stone to investigate the role of social interactions for conceptual knowledge acquisition from PF in more detail.

References

Chi, M. T. H. & Wylie, R. (2014). The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes. *Educational Psychologist, 49*(4), 219-243.

Collins, A. (2012). What is the most effective way to teach problem solving? A commentary on productive failure as a method of teaching. *Instructional Science, 40*, 731-735.

Deiglmayr, K., Rummel, N., & Loibl, K. (2015). The mediating role of interactive learning activities in CSCL: An Input-Process-Outcome model. In: O. Lindwall, P. Häkkinen, T. Koschman, P. Tchounikine, & S. Ludvigsen (Eds.). *Exploring the Material Conditions of Learning: The Computer Supported Collaborative Learning (CSCL) Conference 2015, Vol. 2* (pp. 518-522). Gothenburg, Sweden: International Society of the Learning Sciences.

Dillenbourg, P. (1999). What Do You Mean by "Collaborative Learning"? In P. Dillenbourg (Ed.), *Collaborative Learning. Cognitive and Computational Approaches*. Amsterdam & Boston: Elsevier.

Johnson, D. W., & Johnson, R. T. (2002). Social interdependence theory and university instruction. Theory into practice. *Swiss Journal of Psychology*, *61*(3), 119-129.

Johnson, D. W., & Johnson, R. T. (2009). An Educational Psychology Success Story. Social Interdependence Theory and Cooperative Learning. *Educational Researcher*, *38*(5), 365-379.

Kapur, M. & Bielaczyc, K. (2012). Designing for productive failure. *The Journal of the Learning Sciences, 21*(1), 45-83.

Kapur, M. & Kinzer, C. K. (2009). Productive failure in CSCL groups. *International Journal of Computer-Supported Collaborative Learning, 4*(1), 21-46.

Kapur, M. (2012). Productive failure in learning the concept of variance. *Instructional Science, 40*(4), 651-672.

Kapur, M. (2014). Productive Failure in Learning Math. *Cognitive Science, 38*(2014), 1008-1022.

Loibl, K. & Rummel, N. (2014). Knowing what you don't know makes failure productive. *Learning and Instruction, 34*, 74-85.

Mazziotti, C., Loibl, K, & Rummel, N. (2015). Collaborative or Individual Learning within Productive Failure: Does the Social Form of Learning Make a Difference? In O. Lindwall, P. Häkkien, T. Koshmann, P. Tchounikine & S. Ludvigsen (Eds.). *Exploring the Material Conditions of Learning: The Computer Supported Collaborative Learning (CSCL) Conference 2015, Vol. 2* (p. 570-575). Gothenburg, Sweden: International Society of the Learning Sciences.

Moshman, D. (1982). Exogenous, Endogenous, and Dialectical Constructivism. *Developmental Review, 2*, 371-384.

Mugny, G., & Doise, W. (1978). Socio-cognitive conflict and structure of individual and collective performance. *European Journal of Social Psychology*, *8*, 181-192.

Piaget, J. (1977). *The development of thought: Equilibration of cognitive structures*. Oxford (GB): Viking.

Sears, D. A. (2006). *Effects of innovation versus efficiency tasks on collaboration and learning.* Doctoral dissertation, Stanford University, California. Retrieved November 07, 2012, from http://www.stat.auckland.ac.nz/~iase/publications/dissertations/06.Sears.Dissertation.pdf.

Stahl, G. (2013). Theories of Cognition in Collaborative Learning. In C. E. Hmelo-Silver, A. Chinn, C. K. K. Chan & A. M. O'Donnell (Eds.), *The International Handbook of Collaborative Learning* (pp. 74-90). New York, NY & London, UK: Routledge.

Teasley, S. D (1997). Talking About Reasoning: How Important Is the Peer in Peer Collaboration. In L. B. Resnick, R. Säliö, C. Pontevorvo & B. Burge. *Discourse, Tools, and Reasoning. Essays on Situated Cognition* (pp. 361-384). Berlin: Springer.

Van Boxtel, C., van der Linden, J. & Kanselaar, G. (2000). Collaborative learning tasks and the elaboration of conceptual knowledge. *Learning and Instruction, 10*(2000), 311-330.

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