Collaborative or Individual Learning within Productive Failure: Does the Social Form of Learning Make a Difference?

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Abstract: Productive Failure (PF) – comprising initial problem solving and delayed instruction – has been proven effective for learning when compared to Direct Instruction (DI) in multiple studies with high school and university students. Although the problem-solving phase is usually implemented in a collaborative setting, the role of collaboration for the effectiveness of PF remains unclear. In two quasi-experimental studies we investigated whether collaborative as compared to individual learning in PF leads to more learning. We also tested whether the beneficial PF effect could be replicated with much younger students, namely 4th and 5th graders, than previous studies. Only our first study replicated the PF effect. While the first study did not reveal differences between collaborative and individual learning, in the second study individual learners even outperformed their collaborative counterparts in both PF and DI conditions. Against these findings, we discuss possible prerequisites for PF and propose an agenda for follow-up CSCL research.

Keywords: collaborative learning, productive failure, instructional design

Introduction

Learning approaches in which instruction is delayed, such as Productive Failure (PF; e.g., Kapur, 2012), enable students to explore the underlying concepts and procedures of new learning material on their own before receiving explicit instruction. In the first phase of PF, students try to solve a yet unfamiliar problem, usually in small groups. In the second, so-called instruction phase, the teacher builds upon students' initial solutions to introduce the canonical solution (e.g., Loibl & Rummel, 2014). Multiple studies showed advantages of PF over so-called direct instruction conditions (DI), particularly on the acquisition of conceptual knowledge or transfer (e.g., Kapur, 2012). While the term "direct instruction" is used vaguely in the literature, here we refer to direct instruction as a teacher-lead activity of comparing and contrasting students' erroneous solution attempts with the canonical solution preceding students problem solving (cf. Loibl & Rummel, 2014).

While the effects of delaying instruction are well studied (e.g., Kapur, 2012; Loibl & Rummel, 2014), the role of collaboration within PF has not yet been investigated intensively. As collaborative learning is known to elicit elaborative processes (e.g., Teasley, 1995), it can be hypothesized that collaborating during the problem-solving phase of PF will lead to higher learning outcomes than individual learning. This assumption is also supported by Chi's ICAP-framework (2009) which predicts a superiority of collaborative-interactive learning activities over individual-constructive learning activities. However, research on collaborative learning (e.g., Fischer et al., 2010) has also revealed that collaborating students need to be supported (e.g., by implementing a group goal and/or a role script; cf. Slavin, 1996; King, 2007) in order to ensure fruitful collaborative processes. Against this background, we hypothesized that *supported* collaborative learning leads to higher learning outcomes than individual learning during the problem-solving phase of PF (hypothesis 1).

Our second focus was on replicating the PF effect with younger students: While most PF studies were conducted with high school students (e.g., Kapur 2012; Loibl & Rummel, 2014), we were wondering whether younger students would similarly benefit from PF. This question is of relevance, because the German standards for teaching mathematics highlight the importance of facilitating students' self-determined problem-solving competencies already in primary school (Kultusministerkonferenz, 2004). However, as the findings of Kroneberger and Souvignier (2005) suggest, younger students may be limited in their ability to elaborate deeply on new concepts. Therefore, the beneficial effect of PF found with high school students may not necessarily hold true for younger students. Nevertheless, we hypothesize that the PF effect can be replicated with 4th and 5th graders (hypothesis 2), because so far the beneficial effect of PF was stable across different domains and populations (i.e., students with different ability profiles).

Method

We tested our hypotheses in two quasi-experimental studies. Our initial study (N = 52 4^{th} graders) compared students who worked collaboratively (PF-Coll) or individually (PF-Ind) (cf. hypothesis 1) on an equivalent fraction problem and then received instructions. In order to test hypothesis 2 we additionally implemented a DI-Coll condition, in which students first received instruction and then solved a similar equivalent fraction problem. For our second study, we recruited a larger sample (N=228 5^{th} graders). In this study, we varied the two factors social form of learning (collaborative vs. individual) and the timing of instructions (PF vs. DI) in a 2x2 design, resulting in four experimental conditions (PF-Coll, PF-Ind, DI-Coll, and DI-Ind). Note that across both studies all participants learned during two learning phases: a problem-solving phase and an instruction phase which will be described below.

Problem-solving phase

In the PF conditions, students were challenged with a typical PF problem during the initial problem-solving phase. A PF problem has to address at least two design requirements (cf. Kapur & Bielazcyc, 2012). First, a typical PF problem should allow students to find multiple solution approaches and to elaborate on their (often erroneous) solution ideas. Second, typical PF problems are complex problems which should neither over- nor under challenge the students. The complexity of a problem is based on the interaction between students' prior knowledge and the problem itself. The two requirements were met as follows: The equivalent fraction problem required students to equally divide two "groups" of pizzas for two groups of children (4 pizza Salami ordered for 6 boys and 2 pizza Hawaii ordered for 3 girls) and asks them whether a single boy or girl receives a greater proportion of pizza. This problem can either be solved by calculating a solution, making use of a graphical representation (i.e. circle), drawing various solution ideas or by logical reasoning. Across both our studies, students have not yet been formally introduced into the concept of equivalence nor the procedure to find equivalences (i.e., reducing or expanding fractions) but have already developed a pre-concept of fractional numbers (i.e., numbers smaller than 1). The complexity of the to-be-solved problem was further ensured by including more than a single problem-solving step (i.e., three problem-solving steps): Students had to identify the number and the size of pizza slices each boy or girl receives, and then they had to compare the proportions by expanding or reducing the given fractions.

In the DI condition, students worked on an isomorphic problem during the problem-solving phase. However, as the problem-solving phase only took place after the instruction, they were not expected to generate multiple (erroneous) solutions.

During the problem-solving phase, students either worked alone (PF-Ind and DI-Ind) or in pairs (PF-Coll and DI-Coll). As fruitful collaborative interaction needs to be supported, we introduced a role script and a group goal within the PF-Coll and the DI-Coll condition (cf. Slavin, 1996; King, 2007). The goal of the role script was to support the *collaborative* interaction between learning partners and *not to cognitively* support the problem-solving process (cf. Westermann & Rummel, 2012) The role script consisted of two roles. While the student in the role of the thinker was asked to explain his or her problem-solving ideas to her or his learning partner, the student in the role of the asker was prompted to pose hint-questions and questions of clarification. During collaborative problem solving students were provided with role cards displaying either the role of the thinker or asker and were asked to switch roles (at least once). Thus, students were prompted to collaborate following the role script, but were not forced to do so. We implemented the role script in this way in order to prevent a motivational loss due to over-scripting. By additionally implementing a group goal we aimed to set students a motivational incentive to indeed engage in team work and mutual support. Thus, the experimenter hold out the prospect to win a prize (i.e., chocolate bars) for the dyad who best collaborates.

Instruction phase

The instruction phase was designed as a class discussion and was managed by the experimenter in all conditions. As a starting point students were asked an estimation question whether a single girl or a boy will receive exactly, more or less than an entire pizza (cf. last problem-solving step), because the Rational Number Project (e.g., Cramer, Post & del Mas, 2002) showed that including estimation questions prior to operating with fractions facilitates learning.

In line with the design requirements described in Kapur and Bielaczyc (2012) and with findings of Loibl and Rummel (2014) the instruction built upon "typical" erroneous and incomplete students' solutions which were previously collected in a pilot study (N= 25). By referring to "typical" incomplete students' solutions and not to the very solutions of these students, we ensured to keep the instruction constant across all conditions (of both studies). The experimenter helped students to compare and contrast the typical solutions with the canonical solution for each problem-solving step and explained why the typical solutions are erroneous.

For example, the first problem-solving step implied to identify the number and size of pizza each boy should receive when there are four pizzas but six boys. When equally divided each boy should receive 4/6 (= canonical solution). As one "typical" erroneous student solution was to partition the four pizzas in quarters (instead of sixths) the experimenter can build upon this solution attempt by also dividing four pizzas into quarters, counting the number of slices and dividing the total number of slices by six (16 : 6 = 2 rest 4). According to this solution attempt two boys will receive only two slices of pizza but four boys will receive three slices of pizza. By drawing students' attention to the fact that the pizzas are not yet equally and fairly divided, the experimenter can optimally prepare students for the canonical solution. To further support students understanding about fractions (e.g., Cramer Post & del Mas, 2002) we additionally included working with graphical representations (i.e. circles) as most of students solution attempts also included circles.

Instruments and measures

Across both studies, students were asked to complete a pre- and a posttest. The pretest measured students' mathematical prerequisites such as naming fractions when differently represented and dividing with rest. By measuring students' prerequisites we additionally prevented to prompt *all* students to generate solution ideas about the target concepts and procedures in the pretest as this would reduce the difference between our experimental conditions (i.e. also students from the DI conditions would be prompted to generate solution ideas prior to instruction) (cf. Kapur, 2012; Loibl & Rummel, 2014). To measure students' learning about the concept of equivalence and the procedures for finding equivalence, for the first study we administered a posttest with six items (including a total of 18 subtasks with a maximum total score of 26 points). Based on the results of the first study, we adapted the degree of difficulty of the posttest for the second study. The posttest again included six items (this time including a total of 12 subtasks with a maximum total score of 17 points). In addition to the pre- and posttests in both studies we collected collaborative process data in order to be able to investigate interaction processes. The analysis of the process data is, however, not in the scope of the current paper.

Procedure

In both studies, all participants answered the pretest (circa 10-15 minutes) in the mathematics lesson preceding the respective study. At the beginning of both studies, all students first received a 10-15 minutes introduction about the background and procedure of the study. Students in the PF-Coll and DI-Coll conditions further received explanations about the group goal and a brief role play in order to learn how to make use of the role script. While students in the PF-Coll and PF-Ind conditions started with the problem-solving phase and then received instruction, students of the DI-Coll and DI-Ind conditions first received instruction and then solved an isomorphic problem. The problem-solving phase took 30 minutes and the instruction phase 45 minutes. After both learning phases students had 45 minutes time to work on the posttest.

Results

To assess differences in learning outcomes between the three experimental conditions of the first study, we calculated an ANCOVA with the factor condition, the covariate pretest score, and students' posttest scores as dependent variable. Means and standard deviation of the pretest and posttest scores of the three conditions are displayed in Table 1. We defined two a priori contrasts in line with our hypotheses. One a priori contrast compared PF-Coll and PF-Ind to test the effect of collaboration. Contrary to our first hypothesis, this a priori contrast did not reveal significant differences between PF-Coll and PF-Ind ($F[1,48]=0.4$, $p=.84$). In light of the aforementioned literature not finding a difference between collaborative and individual learning within PF was unexpected. The second a priori contrast compared both PF conditions to the DI condition to test if the PF effect could be replicated with young children (hypothesis 2). Indeed, our results revealed a significant advantage of PF over DI on the learning outcome ($F[1,48]=4.6$, $p=.03$, $\eta_p^2=.09$).

Table 1: Means and standard deviation of pretest and posttest scores (study 1)

	Pretest		Posttest		
	M	**SD**	**M**	**SD**	**N**
PF-Coll	4.5	2.63	7.88	5.43	16
PF-Ind	5.12	1.9	7.71	3.29	17
DI-Coll	5.68	1.29	5.26	3.91	19

For the second study we calculated a two-factorial MANCOVA with the two factors social form of learning (collaborative vs. individual) and the timing of instructions (PF vs. DI), with students' pretest scores as covariate, and students' posttest scores as dependent variable. Means and standard deviations of the second study are displayed in Table 2. We found a significant main effect of the social form of learning (F[1, 223]=3.95, p=.048, η_p^2= .02): overall students learning individually outperformed students learning collaboratively. In testing our second hypothesis we did not find a significant difference between the PF conditions and the DI conditions (F[1,223]=0.74, p=.392,). Also, the interaction between the two factors was not significant (F[1, 223]=0.21, p=.651).

Table 2: Means and standard deviation of pretest and posttest scores (study 2)

		Pretest		Posttest		
Timing of instruction	**Social form of learning**	**M**	**SD**	**M**	**SD**	**N**
PF	individual	4.0	2.04	10.80	2.41	49
	collaborative	4.19	2.48	10.31	2.45	74
	total	4.11	2.31	10.51	2.44	123
DI	individual	4.4	2.46	11.28	2.15	48
	collaborative	4.74	2.25	10.50	2.73	57
	total	4.58	2.34	10.86	2.50	105
Total	individual	4.2	2.25	11.04	2.29	97
	collaborative	4.43	2.39	10.40	2.57	131
	total	4.33	2.33	10.67	2.47	228

Conclusion and discussion

In conclusion, our two quasi-experimental studies revealed divergent findings: While we were able to replicate the beneficial effect of PF for a younger age group in the first study, we were not in the second study. In addition, we did not find a superiority of collaborative learning during the problem-solving phase in PF over individual learning on the posttest scores. Against the background of the literature on collaborative learning (e.g., Chi, 2009; Teasley, 1995), this result is surprising. In the following, we discuss three possible explanations.

Quality of collaboration

As mentioned earlier, collaboration does not automatically lead to fruitful interactions between students. Possibly, despite the collaborative setting, students did not collaborate well enough and may for instance have mostly engaged in individual-constructive learning activities (e.g., one partner generating ideas without considering his partner's understanding) in our collaborative conditions. This activity pattern was possible, because the implemented role script was optional. While the role script intended to facilitate collaborative-interactive activities, students could still engage in merely individual-constructive learning activities. This explanation can be investigated by intensive process data analysis and by comparing whether students who acted strictly in their roles reached higher posttest scores than those who did not. In addition, it is also possible that our participants were not sufficiently familiar with applying the role script in particular and with collaborative learning practices in general as such practices are often not well established in German classrooms and mathematics lessons at this young age. However, as the educational standards of mathematical education (Kultusministerkonferenz, 2004) point out that even at this young age students should be able to collaborate and communicate their mathematical reasoning, this finding underlines the need to pay particular attention to this apparent deficit. However, considering that our first study failed to find a superiority of collaborative learning and the second study even showed a superiority of individual learning it may be useful in moving forward to also discuss our results from another possible angle:

Production blocking

To some extent the problem-solving phase of PF resembles a brainstorming activity, as students try to come up with as many solution ideas as possible for a problem they don't know how to solve yet. The brainstorming literature predicts a superiority of individual over collaborative brainstorming (Stroebe & Nijstad, 2004), because during collaborative brainstorming the generation of associated solution ideas is blocked by turn taking: one partner needs to wait until it is his or her turn before being able to propose a solution idea (cf. production blocking). In order to shed more light on the brainstorming hypothesis an intensive analysis and comparison of the quantity and quality of students' solution attempts in both PF-conditions is needed.

Prerequisites. An additional goal of our studies was to investigate whether the beneficial PF effect also holds true for students of a younger age group. While the results of our initial study confirmed this hypothesis, we were not able to replicate the PF effect that has consistently been found in many previous studies (e.g., Kapur, 2012; Loibl & Rummel, 2014) in our second study. Our divergent findings emphasize the need to discuss in more detail the prerequisites for effective PF. In this context, prior knowledge activation has been discussed as one effective learning mechanism underlying PF (e.g., Loibl & Rummel, 2014). Our participants may not have had enough prior domain knowledge to generate different solution ideas on their own, and may in contrast to older students also not have had enough prior knowledge about metacognitive and motivational learning strategies for adapting to the specific challenges of the PF problem-solving phase. Thus, our results support the notion that the delineation of productive and unproductive failure is a narrow line that one must walk carefully.

In order to shed light on the above considerations we intensify our effort to analyze the process data of the collaborative conditions as well as to analyze students' solution attempts in both PF conditions.

Outlook

In parallel to further analyzing the data of the two presented studies, we plan a follow-up study which will be embedded in a CSCL setting. In particular, we propose to introduce an exploratory learning environment (ELE) when students are confronted with an equivalent fraction problem in the problem-solving phase of PF (followed by instructions in a regular classroom setting). Within an ELE students are enabled to explore the target concepts on their own by inspecting and manipulating, for instance, different representations of fractions and their relationships (e.g., Hoyles, 1993). As collaborating students will work simultaneously from two different computers and will interact via a chat tool with each other, we will be able to address the three core issues raised in the discussion: the quality of collaboration, the danger of blocking ideas (cf. brainstorming research), and the potential influence of students' prior knowledge about metacognitive and motivational strategies.

First, we concluded that the collaboration itself and the collaboration support that was provided (i.e., role script and group goal) may not have developed their full potential, because students were not familiar with collaborative practices and the use of a role script. Apart from enabling students to practice good collaboration prior to the problem-solving phase of PF (e.g., by introducing a pre-training), implementing the collaborative problem-solving phase in an ELE allows for a more adaptive approach: based on students' log data and chat data, we can deliver collaboration support prompts when needed. For instance, when students do no chat with each other for a certain amount of time the intelligent component of the ELE could provide students with a prompt encouraging them to think-aloud and exchange their problem-solving ideas or asking them a thought-provoking question (King, 2007). Furthermore, if only one student talks or interacts with the ELE the student can be prompted to help his learning partner and to engage him in the problem-solving process. On a process level, this adaptive support should facilitate interactive learning activities (Chi, 2009) or transactivity (Berkowitz & Gibbs, 1983).

Second, we argued that the problem-solving phase of PF resembles a brainstorming activity. The research on brainstorming suggests that in a collaborative setting the generation of associated solution ideas is blocked by turn takings and waiting time (cf. production blocking, Stroebe & Nijstad, 2004). Thus, collaborative brainstorming as compared to individual brainstorming is less beneficial for developing solution ideas within PF. However, if we can prevent students from production blocking by letting them generate solutions simultaneously instead of waiting for their turns, brainstorming in a collaborative setting may still have beneficial effects on the quantity and quality of solution ideas as learning partners cause mutual cognitive stimulation. In our ELE students should be able type in their solution ideas in the chat tool whenever they want. In consequence, students would not have to wait until it is their turn to bring in their solution ideas without production blocking. Thus, collaborative learning in such a computer-supported setting would also address the line of brainstorming research.

Third, we assumed that our young participants may not have had enough prior knowledge about metacognitive and motivational learning strategies in order to deal with the specific challenges of the PF problem-solving phase. For instance, within the problem-solving phase of PF students are asked to generate as many problem-solving ideas as possible for a problem type they do not know yet. Due to the lack of domain knowledge, they may reach a dead end (of problem-solving) several times and are thus confronted with their own failure. Based on research on self-regulated learning and motivation (e.g., Kuhl, 1987) students need to apply at least four strategies in order to address this failure: control of motivation, control of attention, coping with failure, emotional control. As young learners might still have to improve the application of the aforementioned learning strategies again the intelligent component of the envisioned ELE could help them by delivering prompts facilitating those learning strategies just in time (i.e., when they reach an impasse and stop working on the problem). These prompts may include hints on the aforementioned strategies as well as emotional boosts (cf. Grawemeyer et al., 2015).

In conclusion, transferring the collaborative problem-solving phase of PF from a face-to-face setting to a computer-supported setting (by implementing it in an ELE) will allow to flexibly react and adapt to the young students needs which, in turn, should facilitate the acquisition of conceptual knowledge.

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