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An Exploratory Analysis of Transactive Interaction Patterns in Cooperative Learning Using Sequential Analysis

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Abstract: For cooperative learning to be effective, the quality of student–student interaction is crucial. Interactions, which are transactive in nature, are positively related to students' learning success during cooperative learning. However, little is known about typical interaction patterns during transactive interaction in face-to-face cooperative learning. Therefore, the current study aims to analyze typical interaction patterns of transactive interaction in cooperative learning. Sixty-eight students from seventh to tenth grade were randomly assigned to a total of 23 groups in their classes. The groups were videotaped while solving the same open-ended mathematical modelling task. The interaction behavior was coded, and interaction patterns were analyzed using sequential analysis with first- and second-order Markov chains. The results indicate that the likelihood that students confirm and pick up correct proposals is relatively high, indicating transactive interaction. However, it is almost equally likely that incorrect proposals are confirmed erroneously, as students barely correct them. Still, students do frequently engage in transactive interaction by discussing incorrect proposals, even though these discussions rarely lead to correct solution approaches. Limitations of these results, as well as the practical implications for cooperative learning in classroom settings, are discussed.

Keywords: cooperative learning; transactive interaction; Markov chains; sequential analysis; interaction patterns

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1. Introduction

Cooperative learning methods are widely used in classroom settings, in which students solve a given problem together in small groups. Key elements of cooperative learning are positive interdependence between the students, meaning that the students can reach their goal only together, and their individual responsibility, that is, each student feeling responsibility for making their individual contribution to the solution of the task [1]. Various studies have shown that cooperative learning can lead to better learning outcomes than individual work [2–5]. However, when comparing the individual studies included in the meta-analysis by Kyndt et al. [4], a heterogenous pattern of results regarding the effectiveness of cooperative learning emerges—reaching positive to even negative effects. These differences in the effectiveness of cooperative learning are partially attributed to the specific methods of cooperative learning used in the different studies (e.g., with or without incentives, task specialization). However, effects vary even within a single method of cooperative learning, so other factors seem to influence the effectiveness as well, such as student age, the domain, the complexity of the task, and the quality of interaction during cooperative learning [4,6–8].

1.1. Interaction during Cooperative Learning

Referring to the offer-and-use model of instruction [8–11], offering students to solve a task together in small groups is a learning opportunity they have to use by engaging in cognitive activities. These cognitive activities manifest in student behavior, e.g., in meaningful interaction with their peers in cooperative learning. Numerous studies have examined students' interaction behavior during cooperative learning and have identified various activities that are effective for learning. According to Kaendler et al. [12], the quality of interaction in cooperative learning can be described on the basis of three dimensions: collaborative, cognitive, and metacognitive activities. Collaborative activities refer, among other things, to the extent to which learners listen to each other, share information, cooperate with each other, and encourage other group members. Cognitive activities include activities such as asking task-related questions, giving elaborative explanations [13–15], and explaining and reasoning about their solution approach [16]. Such cognitive activities have been shown to foster learning as they promote the integration of the to-be-learned content into existing knowledge structures, as well as recognizing and correcting prior misconceptions [17,18]. Finally, metacognitive activities include the planning, monitoring, and evaluation of the solution process and individual understanding.

1.2. Transactive Interaction in Cooperative Learning

Notably, cooperative learning allows students not only to engage in interaction activities that enable students to elaborate and reflect on their own knowledge but also to engage in transactive interaction [19]. Berkowitz and Gibbs [20] define transactive interaction as "reasoning that operates on the reasoning of another" (p. 402), meaning that students refer to each other's ideas and transform them into more elaborate ones. Thus, transactive interaction exceeds constructive activities in the sense of Chi and Wylie [21], who define constructive activities as self-constructing knowledge from the learning material without taking the ideas of others into account (e.g., taking notes while reading a text). However, in transactive interaction, students engage in interactive activities [22], meaning that all persons in this interaction contribute to it constructively, leading to newly generated knowledge by interacting. Thus, transactive interaction includes contributions such as paraphrases, critiques, extensions, integrations of different ideas, requests for clarification or elaboration, and answers to such transactive questions [20,23,24]. Former research has shown that students during cooperative learning vividly engage in transactive interaction, but there are distinct differences regarding the engagement in such interaction on the group and individual level [10,25]. Transactive interaction favors deep-level cognitive processing, i.e., it can lead to a deeper elaboration of the learning content and to better learning outcomes for both the actor who elaborated their partner's solution approach and for their partner whose idea has been elaborated [24]. Research studies provide evidence for the relevance of transactive interaction during cooperative learning for learning: paraphrasing group members' ideas; sharing solution approaches; asking for more detailed explanations; and discussing, correcting, and integrating the different solution ideas, as well as further developing them, have been shown to be related to learning success [26–31].

Hänze and Jurkowski [22] subdivide transactive utterances into low-transactive and high-transactive ones. Low-transactive utterances include, e.g., paraphrases and inquiries, which can benefit the comprehension of all group members. High-transactive utterances, such as questioning or rejecting others' solution ideas and further developing the solution approaches of group members, can explicitly help students to move forward in their solution process. Vogel et al. [26] have shown that the amount of engagement in dialogic transactivity during computer-supported peer learning, i.e., taking the idea of a group member into account by using or extending it, is not related to learning outcome, while dialectic transactivity, i.e., critiquing or integrating different contributions, is positively related to learning. The results provide evidence that the effect of engaging in transactive interaction might vary regarding the concrete transactive activity and how far this activity leads to more profound elaboration.

Barron's [27] findings add a more subject-related perspective to the rather structural perspective on transactive interaction and support the relevance of interactions, which are transactive in nature. She has shown that neither sixth graders' prior knowledge nor the total amount of incorrect and correct proposals during small-group work in mathematics are related to the learning success of the groups. However, the number of solution approaches linked to one another differentiated low-achieving from high-achieving groups. Moreover, she showed that in successful groups, correct proposals were more often accepted and discussed than in less successful groups. In contrast, correct proposals were more often discarded or ignored in less successful groups than in successful ones. In addition, the correct solution approaches should not only be discussed and integrated; how students deal with incorrect solution approaches is also relevant, as the results of Barnes' [32] qualitative study with eleventh graders working in small groups in mathematics illustrate: "For collaborative learning to be effective, groups need to contain some people who question the usefulness of suggestions or the validity of arguments, look for alternative methods, seek clarification of inadequate explanations, and point out flaws in reasoning and inaccuracies in calculations" (p. 9).

In sum, transactive interaction during cooperative learning—in which students, e.g., share and discuss their solution approaches, further develop each other's ideas, integrate useful solution approaches, and question and correct incorrect ones—is positively related to individuals' learning success as well as to group outcome. However, transactive utterances, and especially high-transactive utterances, are cognitively challenging, and it remains unclear under which conditions students are willing to engage in these transactive interactions [22]. Moreover, there is a lack of research regarding interaction patterns in transactive interaction in face-to-face cooperative learning.

1.3. Analyzing Student Interaction in Cooperative Learning with Sequential Analysis

In most cases, the analysis of interaction in cooperative learning is based on the categorization of single events [33]. However, the structure of interactions themselves is sequential: by interacting, individuals influence each other. Thus, one event in an interaction process cannot be considered without the former one(s). Moreover, single-event analyses do not provide the possibility to analyze interaction patterns and, thus, to obtain an insight into transactive interaction during cooperative learning. With single-event analyses, it is not possible to analyze how students deal with competing ideas and arising conflicts, how far they question each other's solution approaches, and how far they build upon each other's ideas.

Next to, for example, network analysis [10,34], sequential analysis can help to analyze interaction sequences quantitatively. With this method, transitional probabilities from one event to another can be determined [35]. Markov chains provide the opportunity to describe typical interaction patterns and how individuals refer to each other. Thus, it is a suitable method to analyze interaction patterns in transactive interaction in cooperative learning. In the context of computer-based collaborative learning (CSCL) settings, this method has already been successfully applied to explore interaction patterns [36–39], while research on using this method on face-to-face peer interaction in school settings is scarce. In the following two sections, we will further introduce the application and potential benefit of using first- and second-order Markov chains when analyzing interaction patterns in cooperative learning.

1.3.1. First-Order Markov Chains

First-order Markov chains calculate the probability of the occurrence of the target event depending on the given event. Thus, typical sequential patterns can be determined. Initially, the absolute frequencies of each response type to each type of event are counted (for a detailed explanation of the procedure, see [35,40]). Based on these absolute frequencies, the transitional probabilities, that is, the relative frequencies of one response type to one type of event, are calculated. For example, when ten questions were asked during cooperative learning, of which four were answered correctly and six incorrectly, the transitional probability of a correct answer following a question would be 4/10 = 0.40, and for incorrect answers, 6/10 = 0.60. A shortcoming of such first-order Markov chains is that the probability of the occurrence of the target event only depends on the event that immediately occurred previously (given event). However, interactions do not only consist of two-event sequences. It can be expected that the target event is dependent not only on the previous one but also on longer sequences. Therefore, an extension to nth-order Markov chains is promising. The higher the number of events in an analyzed sequence, the more rapidly the required sample size increases, so we will only elaborate on second-order Markov chains in the following.

1.3.2. Second-Order Markov Chains

In contrast to first-order Markov chains, second-order Markov chains do not only trace the occurrence of the target event back to the event that occurred immediately previously. Three-event sequences are the basis of the analysis using second-order Markov chains. The transitional probability for the occurrence of the target event following the given event is contingent on the former event. The expected advantage of second-order Markov chains is demonstrated in the following example:

Using first-order Markov chains as in the fictive example above, the probability of a correct answer after a question was 40%, and the probability of an incorrect answer was 60%. However, it can be assumed that the transitional probabilities for correct and incorrect answers are related to whether the question is asked following a correct or incorrect declaration, as the notional example in Figure 1 shows:

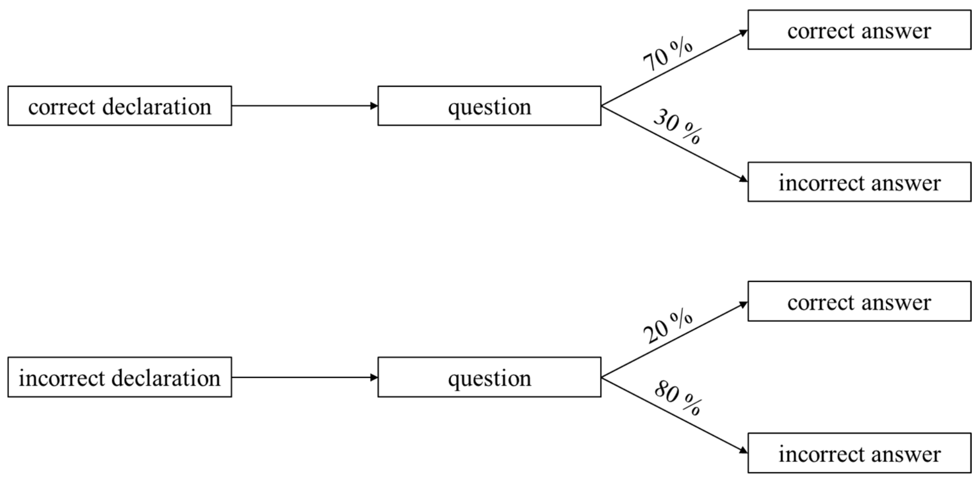


Figure 1. Example of second-order Markov chains.

In this fictive example, the likelihood of correct answers (target event) to a question (given event) that was asked following a correct declaration (former event) was 70% and thus higher than for questions asked after an incorrect declaration (20%). In contrast, the likelihood of incorrect answers after a question following an incorrect declaration was 80% and therefore higher than the likelihood of incorrect answers to questions asked after correct declarations (30%). Similar conditional dependencies on whether the former event is correct or incorrect might also apply to the transitional probabilities between other interaction events.

1.4. The Present Study

Transactive interaction, including discussing conflicting views, clarifying flaws in reasoning, questioning the ideas of other group members, and finally, integrating the (correct) ideas of others in the ongoing solution process, seems to be crucial for promoting learning in cooperative learning settings. Even though much research has been performed on learning-supportive interaction behavior, less is known about typical interaction patterns in cooperative learning. It is unclear how students engage in transactive interaction during face-to-face cooperative learning. Under which conditions do students further develop each other's ideas, reject or confirm solution approaches by other group members, and ask questions and provide answers, and how do students deal with correct or incorrect utterances? In order to fill this research gap, this study aims to exploratively take a closer look at interaction patterns during transactive interaction in cooperative learning using sequential analysis.

2. Materials and Methods

2.1. Design and Participants

The study took place in the middle of the 2015/2016 school year [41]. The sample consisted of 68 seventh- to tenth-graders from one comprehensive school in Germany. The students were videotaped while working face-to-face on the same mathematical modelling task in small groups of two to four students. It was a convenience sample, which should be considered when interpreting the results of this study.

Of the students, 28% were in seventh grade, 21% in eighth grade, 22% in ninth grade, and 29% in tenth grade. About half of the students were female (45%). On average, the students were 14.09 (SD = 1.29) years old. The students were randomly assigned to groups in their classes. In total, 23 groups were formed: two groups of two, twenty groups of three, and one group of four students. The group compositions were gender-heterogeneous (73%) and homogeneous (27%).

Cooperative learning was structured using the think–pair–share method [42]. The lessons were held by a teacher of the research team who did not know the classes and who was instructed to intervene as little as possible during the group work. Although previous research emphasizes the role of teachers during cooperative learning in the form of adaptive teacher interventions [43,44], we chose to minimize teacher interventions because we were interested in students' transactive interaction behavior without teacher interventions. The lesson was structured through an introductory phase, in which the teacher explained the task; an individual work phase for about 10 min, in which the students dealt with the task individually and developed initial solution approaches (think phase); a subsequent group phase, in which the students shared their understanding of the task and their solution approaches and jointly solved the task (pair phase); and a plenum phase, in which some of the groups presented their solutions (share phase). The mathematical modelling task shown in Figure 2 was taken from Herget [45] (pp. 189–190).

The different levels of mathematical competence between the grades were compensated for by providing additional task-relevant information for students from grades seven and eight, whereas students from grades nine and ten had to gather this information by themselves (see Figure 2). Only the pair phase (M = 25.56 min, SD = 3.67 min) was considered in the following analyses.

The Football-Globe

Until the Football World Cup 2006, a walk-in football-globe travelled throughout all 12 venues of the World Cup.

© Archiv Büro André Heller

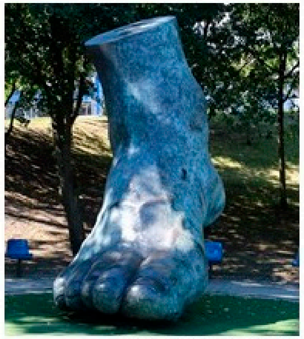
In this giant football, events following the motto „Cultural festival in the World Cup-Globus" were organized.

The oversized football was illuminated at night and then represented a globe.

a) How tall would a football player be who could play with this ball?

b) How long would a football field be on which one could play with the football?

Uwe Seeler: World's biggest foot



© Beate Eckert-Kraft
(Eckert-Kraft, 2016)

A giant Uwe-Seeler bronze foot welcomes the football fans at the entrance of the arena in Hamburg.

The bronze foot is 3.50 meters high, 2.30 meters wide, and 5.50 meters long and weighs 1.5 tonnes. Currently, it is being examined whether the sculpture can get an entry in the Guinness Book of Records as the World's biggest foot.

c) Does this foot fit to the football player from task a)?

Further information

Excerpt of the football rules

A ball is in accordance with the rulse if

- it is spherical,
- it is made of leather or other suitable material,
- it has a circumference of not less than 68 cm and not more than 70 cm (corresponding to a diameter between 21.6 cm and 22.2 cm; additionally in grade 7 and grade 8).

The football field:

- The football field must be rectangular.
- The length of the sidelines must be greater than the length of the goal line.
- Length: not less than 90 m, not more than 120 m
- Width: not less than 45 m, not more than 90 m
- International matches:
  - Length: not less than 100 m, not more than 110 m
  - Width: not less than 64 m, not more than 75 m

Figure 2. The football globe task [45]. Picture of the football globe was reprinted with permission from Archiv Büro André Heller [46]. 2006, André Heller. Picture of the bronze foot was reprinted with permission from Eckert-Kraft [47]. 2016, Beate Eckert-Kraft.

2.2. Video-Based Analysis of Student–Student Interaction

The videos of the groups solving the task cooperatively were used to categorize the students' interaction behavior. The analysis was conducted by two trained coders and a master coder who developed the coding manual. They coded the videos independently using the program Videograph [48]. In the first step, the pair phase was coded by separating it from the think and share phases. Subsequently, each student's turn during the pair phase was identified and categorized following a standardized coding manual concerning the following categories: task relation, function, reference, directness of reference, syntactic classification, type of question, type of declaration, and correctness. Following Jurkowski and Hänze's understanding of transactive interaction during cooperative learning, self-referential turns were not considered as having a reference to another turn [29,30]. The coding scheme is systematically shown in Figure 3.

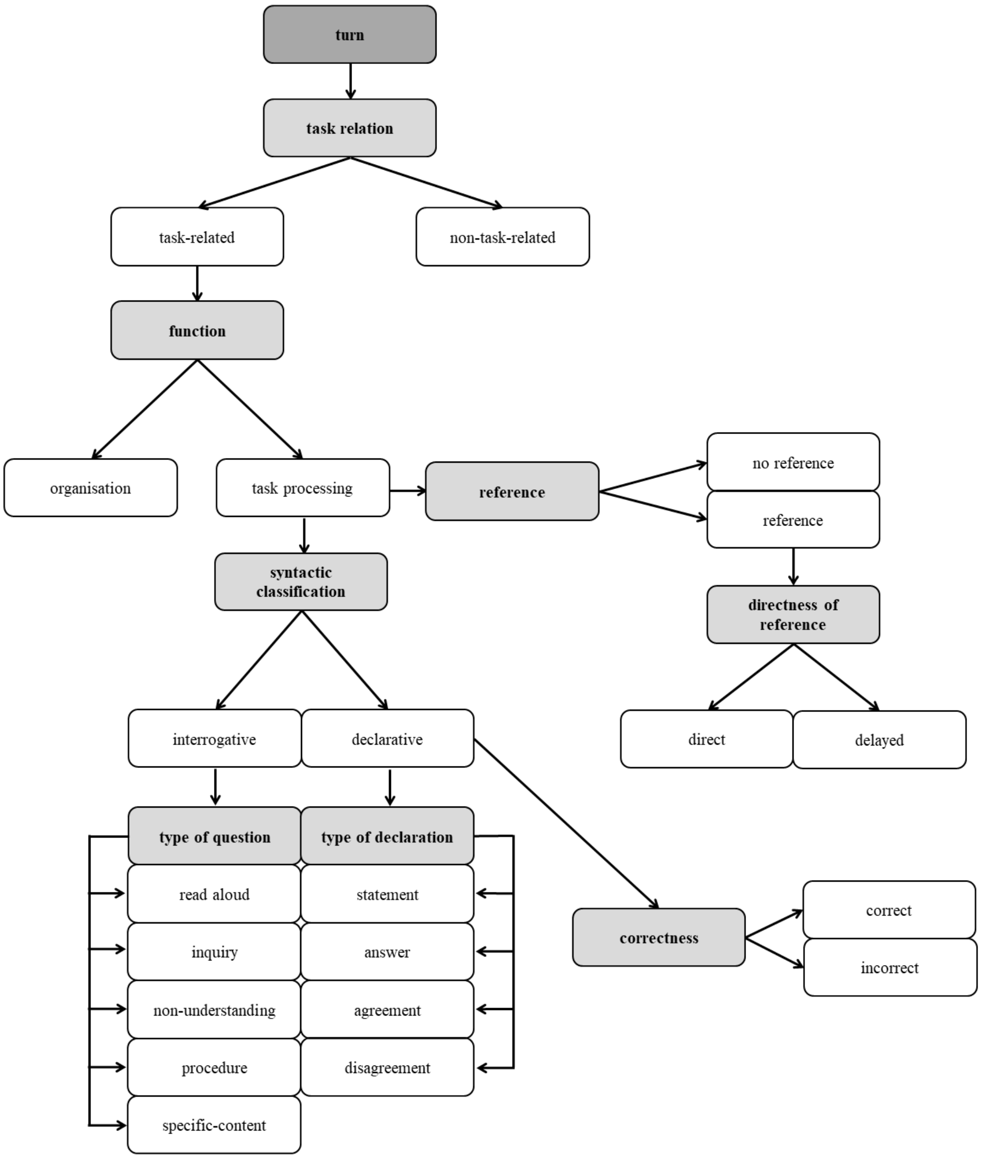


Figure 3. Overview of the categories to analyze students' interaction behavior.

The categories and their coding rules were self-developed or partially adapted from already existing coding systems as shown in Table 1. Each coding system was supplemented by a residual category, including those turns that could not unambiguously be assigned to one of the subcategories.

Table 1. Examples and references of the categories.

Coding System	Subcategories	Example	Literature
turn	/	"A football player is about 1.80 m tall." "What time is it?"	[49]
task relation	task-related	"A football player is about 1.80 m tall."	[50–52]
	non-task-related	"What time is it?"	
function	organization	"I'll go and get my ruler."	[53]
	task processing	"The door fits seven times."	
reference (no self-references)	no reference	"I have calculated how often a human person would fit into the football field." (new idea)	[20]
	reference	S1: "The door fits 8 times." S2: "No, 7 times."	
directness of reference	direct	S1: "A foot length fits ten times into a human person." S2: "No, only 6 times."	own development
	delayed	S1: "How do you calculate the height of a ball?" S2: "We should find out how often the door fits into the ball." S3: "We need to find out the diameter to calculate the height."	
syntactic classification	interrogative	"How did you calculate this?"	[54]
	declarative	"Firstly, we should find out which additional information we need."	
type of question	read aloud	reading/paraphrasing the task	[54–56]
	inquiry	"Do you understand?"	
	non-understanding	"I just don't get it!"	
	procedure	"How should we go on?"	
	content-specific	"Are you sure?"	
type of declaration	statement	"A door is about 2 m high."	own development
	answer	S1: "How tall is a normal football player?" S2: "About 1.90 m."	
	agreement	S2: "About 1.90 m." S3: "Yes, I think so too."	
	disagreement	S2: "About 1.90 m." S4: "No, much smaller! About 1.70 m."	
correctness	correct	"A football player is about 1.80 m tall."	own development
	incorrect	"If we take half of the circumference of the ball, we have its height."	

Four randomly chosen videos were coded by the master coder and the two coders, while the remaining 19 videos were randomly distributed between the two coders. The intercoder reliabilities of the categories were calculated using the percentage of agreement and Cohen's κ over the four videos all three coders coded. The calculation of Cohen's κ was not possible for the categories pair phase and turn since the event only had to be identified and not categorized. The intercoder reliabilities were satisfactory for all categories/coding systems, as shown in Table 2.

Table 2. Intercoder reliabilities of the categories between the master coder and the two coders.

Coding System	Percentage of Agreement	Cohen's κ
pair-phase (begin)	≥91%	/
pair-phase (end)	≥86%	/
turn	≥86%	/
task relation	≥98%	≥0.91
function	=100%	≥0.86
reference	≥93%	≥0.72
directness of reference	≥95%	≥0.72
syntactic classification	≥98%	≥0.93
type of question	≥94%	≥0.83
type of declaration	≥88%	≥0.78
correctness	≥89%	≥0.88

2.3. Data Preparation

Before the analysis was performed, the data had to be prepared. The coded turns of the students were restructured and merged into one variable to be able to detect typical interaction patterns. In sum, 10060 turns in 23 groups were identified. However, only task-related utterances were considered (8329 turns). Because we were interested in how students respond to each other in transactive interactions, all kinds of utterances had to have a direct reference. Thus, it was ensured that the target event did indeed relate to the given event, i.e., the previously occurred event. The only exception were statements, which were also considered when they had no reference. Statements without a reference could indicate new solution approaches so that the transitional probabilities could be used to analyze how new solutions are handled, while statements with a direct reference indicate a pick-up of the given turn into the ongoing solution process. In total, 4851 of 6679 declarations, i.e., statements, answers, agreements, and disagreements, had a direct reference and 1028 of 6679 did not have a direct reference. In addition, it was considered whether the declarations were correct or incorrect, which led to another reduction of the declarations that were considered in the analyses. A total of 3970 out of the 5879 declarations with reference or statements without a reference could be coded as correct or incorrect. Regarding the coding system type of question, only the content-specific questions were part of the analysis since they could represent critical questions (1179 of 1540 questions in total). Those content-specific questions also had to have a direct reference so that they could constitute an immediate response to the former event, which reduced the total number to 772 content-specific questions with a direct reference.

This data restructuring led to 11 category combinations that were part of the following analyses (Table 3). Pick-ups, disagreements, and questions illustrate indicators for transactive interaction. Pick-ups include paraphrasing ideas from other group members, further developments of ideas, and the integration of different solution approaches. By disagreeing or asking content-related questions that indicate critical inquiries, students could contribute to a change in or clarification of the current solution approach. Questions as coded in this study, furthermore, include questions with the goal of clarifying if one has understood the idea of a group member appropriately, questions to gather further information, and critical inquiries. Although the other categories do not represent transactive interaction by definition, they take an important role in the solution process: new ideas and answers can be the starting point of transactive interaction, i.e., by picking them up or disagreeing. Agreements can reinforce the pursuit of a solution approach. Table 3 shows the frequencies of the different categories. Only incorrect pick-ups were not observed, so this category was excluded from the following analyses.

Table 3. Category combinations used in the analyses.

	Correct-Ness	Coding	Category	Absolute Frequencies	Relative Frequencies
1	correct	statement without reference	new idea	202	4%
2		statement with direct reference	pick-up	737	16%
3		answer with direct reference	answer	212	4%
4		agreement with direct reference	agreement	421	9%
5		disagreement with direct reference	disagreement	188	4%
			total correct	1760	44%
6	incorrect	statement without reference	new idea	476	10%
7		statement with direct reference	pick-up	0	0%
8		answer with direct reference	answer	275	6%
9		agreement with direct reference	agreement	442	9%
10		disagreement with direct reference	disagreement	1017	21%
			total incorrect	2210	56%
			total declarations	3970	84%
11		content-specific question	question	772	16%
			total	4742	100%

2.4. Data Analyses

To gain insight into students' transactive interaction during cooperative learning, first- and second-order Markov chains (see Section 1.3) using the described category combinations (Table 3) were calculated. With the first-order Markov chains, the probability of one event following another event (e.g., the probability of a correct answer following a question or a correct disagreement following an incorrect answer) was analyzed. In addition to first-order Markov chains, second-order Markov chains were used, as it can be expected that students' interaction behavior does not only depend on the immediately previous utterance but also on the former event (former event → given event → target event). However, we only included the former event differentiated by its correctness and did not consider the specific category because a much higher number of coded utterances would be necessary to fill the 11^3 = 1331 possible different three-event-sequences. By considering only whether the former event is correct or incorrect, the number of possible three-event-sequences was reduced to 242.

For both first- and second-order Markov chains, z-scores were calculated to detect whether the transitional probabilities were on a 5%-level significantly lower (z-score < -1.96) or higher (z-score > 1.96) than expected using the formula by Bakeman and Gottman [35] (p. 109).

3. Results

3.1. Results of the First-Order Markov Chains

In the first step, the transitional probabilities between the different interaction categories were calculated using first-order Markov chains. Because 4742 category combinations were identified (see Table 3), a total number of 4741 event sequences for the following analysis would have been expected. However, only 3214 event sequences were part of the analysis. This reduction in event sequences is due to incomplete sequences because two-event sequences are needed to calculate the transitional probabilities. These lacks in the data are due to non-completely codable turns (see Section 2.2).

The results are shown in Table 4: The number in each cell represents the transitional probability for each possible event sequence based on the total number of responses to this specific category (last cell in each row). Bold numbers represent transitional probabilities that were significantly higher than expected, and underlined numbers identify transitional probabilities that were significantly lower than expected. For instance, a correct new idea was followed in 23% of cases by a correct pick-up and in 32% of cases by a correct agreement. Both transitional probabilities were significantly higher than statistically expected, while, for example, the transitional probability from a correct new idea to an incorrect disagreement was with 15% significantly lower than expected.

Table 4. Transitional probabilities of the first-order Markov chains.

			Target Event *										
			Correct					**Incorrect**					
			Idea	**Pick-Up**	**Answer**	**Agree**	**Disagree**	**Idea**	**Answer**	**Agree**	**Disagree**	**Quest**	**Total**
Given event	**Correct**	**Idea**	0.02	**0.23**	0.01	**0.32**	0.01	0.07	0.00	0.03	0.15	0.17	117
		Pick-up	0.03	**0.26**	0.00	**0.29**	0.02	0.03	0.00	0.02	0.17	0.18	522
		Answer	0.01	**0.23**	**0.12**	**0.26**	0.05	0.03	0.01	0.01	0.14	0.15	155
		Agree	**0.06**	**0.35**	0.00	**0.23**	0.01	0.06	0.00	0.01	0.17	0.11	268
		Disagree	0.02	**0.22**	0.00	**0.26**	**0.12**	0.01	0.00	0.02	0.22	0.13	143
	Incorrect	**Idea**	0.03	0.07	0.01	0.04	**0.08**	**0.08**	0.01	**0.30**	0.20	0.20	291
		Answer	0.01	0.06	0.03	0.01	0.06	0.07	0.09	**0.23**	**0.27**	0.18	196
		Agree	0.03	0.07	0.00	0.01	0.06	**0.09**	0.01	**0.17**	**0.35**	0.20	269
		Disagree	0.02	0.08	0.00	0.01	**0.08**	0.06	0.00	**0.23**	**0.28**	**0.22**	715
		Quest	0.01	0.11	**0.23**	0.03	0.02	0.04	**0.31**	0.04	0.12	0.11	538
		Total	72	492	153	366	155	174	194	385	667	546	3214

* Bold numbers represent transitional probabilities that were significantly higher than expected. Underlined numbers represent transitional probabilities that were significantly lower than expected. Idea = new idea, agree = agreement, disagree = disagreement, quest = question.

To illustrate the striking interaction patterns, Figure 4 only contains those transitional probabilities between the interaction events that were significantly higher than expected. The following patterns were apparent regarding the handling of correct solution approaches: a correct new idea (given event) was followed in 32% of cases by a correct agreement (target event). The high probability of agreements after correct declarations could also be shown for the other forms of declarations: correct agreements could be determined with 29% after a correct pick-up, with 26% after a correct disagreement, with 26% after a correct answer, and with 23% after a correct agreement. Moreover, correct declarations led to a high rate of transactive interaction in the form of pick-ups: students picked up correct new ideas in 23% of cases, correct agreements in 35% of cases, correct disagreements in 22% of cases, correct answers in 23% of cases, and correct pick-ups themselves in 26% of cases. Thus, it is likely that correct declarations are used for the further solution process, either by confirming them through agreement or by directly picking them up leading to transactive interaction. Another central finding is that no significant transitional probability from a correct proposal to an incorrect one could be found.

Concerning the handling of incorrect proposals, the following significant transitional probabilities were found. Comparable to the handling of correct proposals, students confirmed incorrect proposals with a high probability: incorrect new ideas were followed by incorrect agreements in 30% of cases, incorrect disagreements were agreed with in 23% of cases, incorrect answers in 23% of cases, and incorrect agreements themselves in 17% of cases. Furthermore, the high probability of incorrect disagreements following other incorrect proposals is conspicuous (with 35% after incorrect agreements, with 27% after incorrect answers, and with 28% after incorrect disagreements themselves).

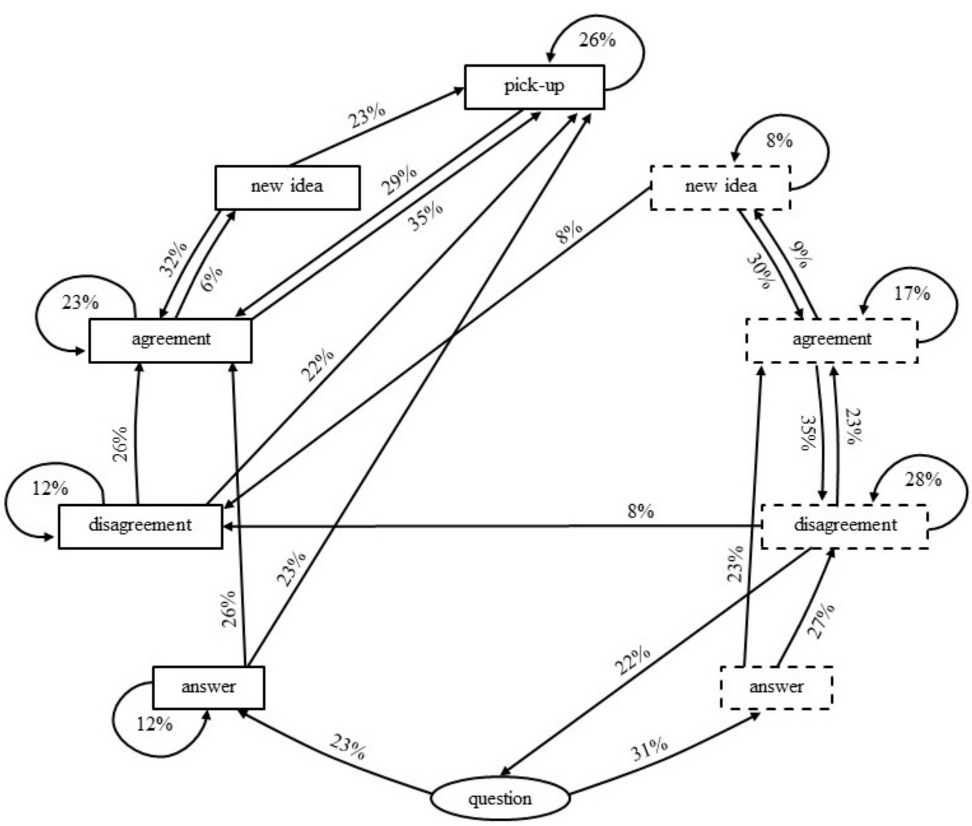


Figure 4. Significant transitional probabilities using first-order Markov chains. Rectangles with continuous outlines represent correct, and rectangles with dotted outlines represent incorrect declarations.

Only two direct and one indirect transitional probability from an incorrect proposal leading to a correct one were found. Correct disagreements followed incorrect new ideas as well as incorrect disagreements in 8% of cases. Moreover, incorrect disagreements were followed by questions in 22% of cases, which could constitute an indirect transition to a correct solution approach. However, questions themselves were more often answered incorrectly, in 31% of cases, than correctly, in 23% of cases. These results illustrate that incorrect declarations can also lead to transactive interaction because students try to convert the wrong solution approach into a correct one by rejecting it. Furthermore, correct disagreements—although they are rare—are then likely to be agreed to or picked up and are thus further used transactively in the solution process.

3.2. Results of the Second-Order Markov Chains

In the second step, the transitional probabilities were calculated using second-order Markov chains. The correctness of the former event was also considered in the calculations, as it could influence the transitional probabilities. Two matrices (see Tables 5 and 6) were generated, including the transitional probabilities—one for correct and one for incorrect former events. Due to the calculation of second-order Markov chains, the number of data that were part of the analysis was reduced. On the one hand, this was due to the necessity of three-event sequences, so incomplete sequences were excluded. On the other hand, the former event was only considered if it was a declaration because its correctness was of interest.

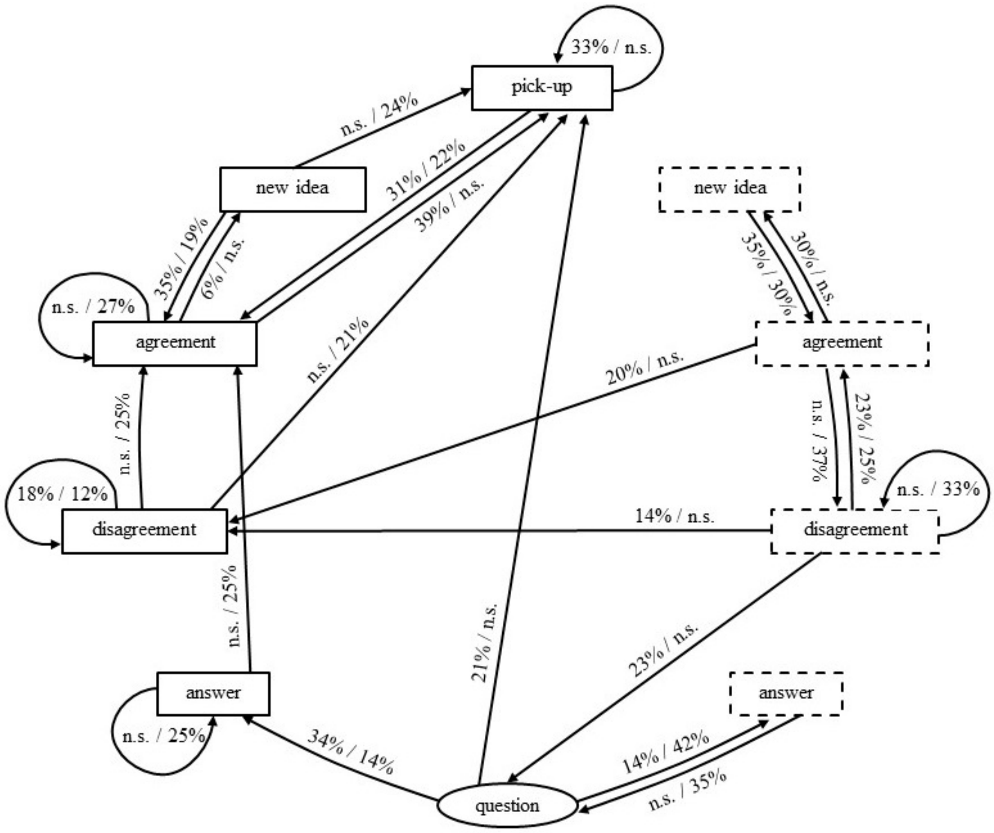


Figure 5. Significant transitional probabilities using second-order Markov chains. The probabilities for a transition between two interaction events with a correct declaration as the former event are given on the left; the probabilities for a transition between two interaction events with an incorrect declaration as the former event are given on the right. Rectangles with continuous outlines represent correct declarations, and rectangles with dotted outlines incorrect declarations. n.s. = non-significant.

Table 5. Transitional probabilities of the second-order Markov chains with correct declarations as the former event.

			Target Event *										
					Correct					Incorrect			
			Idea	**Pick-Up**	**Answer**	**Agree**	**Disagree**	**Idea**	**Answer**	**Agree**	**Disagree**	**Quest**	**Total**
Given event	**Correct**	**Idea**	0.04	0.30	0.00	**0.35**	0.04	0.00	0.00	0.00	0.22	0.04	23
		Pick-up	0.05	**0.33**	0.00	**0.31**	0.02	0.03	0.00	0.01	0.11	0.13	236
		Answer	0.00	0.23	0.00	0.31	0.08	0.08	0.00	0.00	0.23	0.08	13
		Agree	**0.06**	**0.39**	0.00	0.21	0.01	0.06	0.00	0.00	0.15	0.12	210
		Disagree	0.00	0.25	0.00	0.21	**0.18**	0.04	0.00	0.00	0.21	0.11	28
	Incorrect	**Idea**	0.00	0.13	0.00	0.06	0.13	0.03	0.00	**0.35**	0.10	0.19	31
		Answer	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.00** [1]	0.00	1
		Agree	0.00	0.10	0.00	0.00	**0.20**	**0.30**	0.00	0.20	0.00	0.20	10
		Disagree	0.02	0.15	0.01	0.02	**0.14**	0.03	0.01	**0.23**	0.16	**0.23**	154
		Quest	0.00	0.21	**0.34**	0.08	0.02	0.01	**0.14**	0.02	0.09	0.10	133
		Total	28	234	46	151	45	30	20	54	114	117	839

* Bold numbers represent transitional probabilities that were significantly higher than expected. Underlined numbers represent transitional probabilities that were significantly lower than expected. Idea = new idea, agree = agreement, disagree = disagreement, quest = question. [1] Although incorrect answers were followed in 100% of cases by an incorrect disagreement significantly higher than expected, this result has to be viewed with caution: in total, there was only one event following an incorrect answer after a correct declaration, and this single event was an incorrect disagreement. Therefore, this event sequence is not considered in Figure 5.

Table 6. Transitional probabilities of the second-order Markov chains with incorrect declarations as the former event.

			Target Event *										
					Correct					Incorrect			
			Idea	Pick-Up	Answer	Agree	Disagree	Idea	Answer	Agree	Disagree	Quest	Total
Given event	Correct	**Idea**	0.00	**0.24**	0.00	**0.19**	0.00	0.14	0.00	0.05	0.24	0.14	21
		Pick-up	0.02	0.15	0.01	**0.22**	0.01	0.04	0.00	0.02	0.33	0.19	81
		Answer	0.00	0.25	**0.25**	**0.25**	0.00	0.00	0.00	0.00	0.13	0.13	8
		Agree	0.07	0.20	0.00	**0.27**	0.00	0.13	0.00	0.07	0.27	0.00	15
		Disagree	0.02	**0.21**	0.00	**0.25**	**0.12**	0.01	0.00	0.04	0.24	0.12	85
	Incorrect	**Idea**	0.05	0.08	0.00	0.03	0.08	0.07	0.00	**0.30**	0.18	0.20	60
		Answer	0.00	0.06	0.06	0.00	0.06	0.06	0.00	0.06	0.35	**0.35**	17
		Agree	0.03	0.09	0.00	0.00	0.05	0.10	0.01	0.16	**0.37**	0.19	208
		Disagree	0.02	0.07	0.00	0.00	0.05	0.09	0.00	**0.25**	**0.33**	0.17	297
		Quest	0.01	0.09	**0.14**	0.01	0.01	0.06	**0.42**	0.04	0.14	0.09	227
		Total	23	106	36	54	44	76	98	13	281	158	1019

* Bold numbers represent transitional probabilities that were significantly higher than expected. Underlined numbers represent transitional probabilities that were significantly lower than expected. Idea = new idea, agree = agreement, disagree = disagreement, quest = question.

Table 5 shows all transitional probabilities between the different interaction events when the former event was correct. For instance, a correct new idea (given event) was followed in 35% of cases by a correct agreement (target event) if the former event was correct (former event). This transitional probability was significantly higher than expected. Table 6 shows the transitional probabilities between the different interaction events when the former event was incorrect. Here, a correct new idea was followed by 19% by a correct agreement. This transitional probability was also significantly higher than expected.

In Figure 5, the results of the second-order Markov chains with correct and incorrect former events are combined and reduced to those transitional probabilities that were significantly higher than expected. The transitional probabilities for second-order Markov chains with correct former events are given on the left; the transitional probabilities for second-order Markov chains with incorrect former events are given on the right. The percentages can be read as follows: if the former declaration was correct, students disagreed correctly with 20% to incorrect agreements. If the former declaration was incorrect, the transitional probability from an incorrect agreement to a correct disagreement was not significant. If the former declaration was correct, students agreed with 35% to new ideas. If the former declaration was incorrect, students agreed with 19% to new ideas.

The analysis with first-order Markov chains revealed only low transitional probabilities from incorrect proposals to correct ones (Figure 4). When considering the correctness of the former event, the following patterns become apparent: the probabilities of correct disagreements following incorrect proposals were in some cases significantly higher than expected when the former event was correct (20% after incorrect agreements, 14% after incorrect disagreements). However, there were no such significant transitional probabilities from an incorrect declaration to a correct one when the former event was incorrect. This finding might indicate that it is easier for students to engage in transactive interaction leading to a transformation of an incorrect proposal into a correct one by disagreeing correctly when they had already taken a correct solution approach.

Yet it was very likely that the students disagreed incorrectly with incorrect proposals when the former event was incorrect, while these transitional probabilities were only partly significant when the former event was correct (Figure 5). For instance, incorrect agreements were followed in 37% of cases by incorrect disagreements when the former event of this sequence was incorrect. This transitional probability was not significant when the former event was correct. This result, in turn, could indicate that the students recognized the flaws in the interaction process and, therefore, engaged in transactive interaction by disagreeing but were not able to correct them when the former event was incorrect. Comparable with the results of the first-order Markov chains, the results of both second-order Markov chains with correct and incorrect former events again revealed a high rate of incorrect agreements with incorrect proposals. It was very likely that the students confirmed incorrect proposals irrespective of whether the former event was correct or incorrect.

Furthermore, it becomes clear that the high probability of questions after incorrect disagreements (22%; see Figure 4), another way to turn an incorrect proposal into a correct one by initiating transactive interaction, was only significant when the former event was correct (23%). This finding may reveal that students only question incorrect proposals if they already had a correct solution approach. Closely linked with this finding, another noticeable difference was found: using first-order Markov chains, the transitional probability of a correct answer after a question was lower than the probability for an incorrect one (Figure 4). However, when the question was asked following a correct declaration, the probability of a correct answer was with 34% higher than the probability of an incorrect one (14%). In comparison, the likelihood of a correct answer to a question that was asked after an incorrect proposal was with 14% lower than the probability of an incorrect answer (42%).

Comparable with the results of first-order Markov chains (Figure 4), it was very likely that students agreed correctly to correct proposals when using second-order Markov chains. However, there were some differences between second-order Markov chains with correct and incorrect former events. While there were no significant transitional probabilities from a correct answer and a correct disagreement to a correct agreement when the former event was correct, these transitional probabilities were significant with incorrect former events (Figure 5). Thus, students seem to realize that the reinforcement of a correct answer or disagreement is not necessary if they have already followed a correct solution approach, while they reinforce correct answers or disagreements when they occurred after an incorrect solution path. In comparison, the likelihood of correct agreements following correct new ideas (35%) and correct pick-ups (31%) was higher when the former event was correct than when it was incorrect (correct new ideas: 19%, correct pick-ups: 22%). Furthermore, correct pick-ups of correct proposals were again very likely when second-order Markov chains were used. Still, there were some differences depending on whether the former event was correct or incorrect (Figure 5). For instance, correct pick-ups were only then picked up significantly more often than expected (33%) when the former event was correct, while correct disagreements were only picked up more often than expected (21%) when the former event was incorrect.

4. Discussion

The goal of the present study was to investigate exploratorily how students engage in transactive interaction during face-to-face cooperative learning. The analysis with first-order Markov chains revealed that the concrete way students engage in transactive interaction depends on whether they react to a correct or incorrect declaration. While correct declarations do primarily lead to agreements and pick-ups, with the latter representing transactive interaction, incorrect declarations are seldom picked up. Incorrect declarations are instead questioned or disagreed with. However, these questions and disagreements to incorrect proposals only occur and only lead to correct proposals under certain circumstances. The second-order Markov chains revealed that students seemed to only question incorrect proposals if they already had a correct solution approach. Furthermore, these questions were more often answered correctly when they were asked after a correct declaration, while they were more often answered incorrectly when following an incorrect declaration. Disagreements to incorrect proposals, as another transaction with which, in principle, a wrong solution path can be converted into a correct one, only occurred when the former event was correct. This finding might indicate that it is easier for students to transform an incorrect proposal into a correct one by disagreeing correctly when they had already taken a correct solution approach. Moreover, it was very likely that the students disagreed incorrectly with incorrect proposals when the former event was incorrect, while these transitional probabilities were only partly significant when the former event was correct (Figure 5). For instance, incorrect agreements were followed in 37% of cases by incorrect disagreements when the former event of this sequence was incorrect. Although students engaged in transactive interaction by recognizing the flaws regarding the solution approach and disagreeing with it, they were not able to turn it into a correct solution approach when the former event was incorrect. These results illustrate that students seem to be aware that the current solution approach is non-expedient and thus engage in transactive interaction by questioning and disagreeing. However, both transactions seldom lead to a correct solution approach. Moreover, it was very likely that the students confirmed incorrect proposals irrespective of whether the former event was correct or incorrect, leading to a reinforcement of pursuing the wrong solution approach.

In conclusion, students support each other and further develop each other's ideas when reacting to a correct declaration. Regarding incorrect declarations, transactive interaction takes the form of students vividly disagreeing or questioning each other, although this rarely leads to a correct solution approach. Thus, students seem to adapt their way of transacting with each other regarding the correctness of the solution path followed.

4.1. Limitations

Although this study gives a detailed insight into the interaction processes in cooperative learning by using sequential analysis, a few limitations have to be taken into account. First, our coding manual included only three overarching forms of transactive interaction, i.e., pick-ups, disagreements, and questions. Pick-ups include declarations such as paraphrases, extensions, and integrations of ideas. Furthermore, our questions also included different forms of transactions, namely questions with the goal of clarifying if one has understood the idea of a group member appropriately, questions to gather further information, and critical inquiries. To gain a deeper insight into how students engage in transactive interaction, these transacts should be coded separately in future analyses, e.g., [20,23,57]. It would also be possible to analyze the conditions for engagement in low- and high-transactive interaction separately. Second, we had a relatively small sample of 68 students out of only four classes of one school in our study. Moreover, these students were from different grades. Third, the transitional probabilities were calculated over all 23 groups. However, it can be assumed that those may vary between the different groups depending on the group composition. Relating to that, the interaction behavior of the individual students may also depend on the group composition. The individual engagement in discussions, e.g., in how far students agree or disagree with their group members' solution approaches or how often they contribute their own solution approach, may be explained by the ambition for conformity in groups. This ambition for conformity can be triggered by an informational and/or normative social influence [58]. Due to the complexity of the task, some students might have been following the solution approaches of their group members—especially those group members with higher social status [59–61]. Low-status students, e.g., students with a low grade in mathematics or those who are less popular, may more often confirm proposals. In contrast, high-status students may more often disagree—correctly or incorrectly—with the proposed solutions of their group members. However, these assumptions need to be investigated in further research by analyzing how far the individual behavior in cooperative learning is dependent on the social status and the group composition. In order to analyze individual behavior, a much higher number of data is necessary. Even though we calculated the transitional probabilities over all groups, the absolute frequency of some event sequences was quite low, leading to limited generalizability. This problem of a small number of some event sequences might increase when calculating the transitional probabilities on an individual level. Fourth, in future studies, it should be investigated which kind of (transactive) interaction patterns contribute to or negatively affect student learning. Fifth, the transitional probabilities calculated in this study are limited not only to this specific sample but also to the used mathematical modelling task. Thus, further research is needed to investigate whether the found interaction patterns are transferable to other samples, group tasks, and subjects.

4.2. Practical Implications

In summary, our analyses revealed that students further develop correct proposals by their group members or confirm them during transactive interaction. Concerning wrong solution approaches, they frequently discuss or question. However, these discussions rarely led to a correct solution approach in our sample. Still, this might indicate that the students recognized flaws in reasoning and experienced a socio-cognitive conflict between their knowledge and their group members' solution approaches but were not able to transfer the incorrect solution approaches into correct ones.

These findings point to the relevance of teachers for a successful implementation of cooperative learning: Teachers should monitor students' collaborative, cognitive, and metacognitive activities and support them if necessary [12]. Moreover, diagnosing errors and misconceptions seems to be necessary as well. If students do not correct errors by themselves and are not able to transfer an incorrect solution approach into a correct one, teachers should provide domain-specific support, including, for example, feedback, or hints [12]. Such teacher support should be adaptive, i.e., it should match the specific difficulties of the respective group [43]. However, research shows that providing adaptive support during cooperative learning is a challenging endeavor for teachers. Meloth and Deering [62] have shown that teachers' support is rarely adapted to the specific difficulties of learners. This is particularly problematic as teachers' intervention that is not adapted to the group can be accompanied by a deterioration of the quality of student interaction [63]. An additional and promising approach to support student learning can be derived from research on productive failure, which shows that problem-solving prior to instruction can be superior to a sequence of instruction followed by problem-solving [64,65]. Productive failure instructions consist of two phases: in the first phase, students in small groups try to solve a problem, while incorrect solution approaches will (at least in some groups) probably be pursued. In the second phase, the teacher presents the correct solution, contrasting it to typical (incorrect) student solutions. As shown in our study, the students vividly discussed their different solution approaches—even though these discussions rarely led to correct solution approaches. These insufficient solutions would provide a good starting point for a subsequent in-class discussion of the canonical solution, because the students already might have detected knowledge gaps. Still, implementing such an in-class discussion about typical mistakes of the groups while solving the task is challenging for teachers: teachers have to monitor and diagnose students' solution paths to be able to discuss and contrast them afterward.

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