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Learning Arithmetic Word Problem Structure with a Picture Combination Application in Kindergarten

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Abstract: Teaching number sense to kids before elementary school has been researched thoroughly, but there has been a lack of research into teaching the structure of word problems to kids of the same age, despite of their classroom popularity and the trouble students have with them. Our research focuses on creating a textless, image rich application empowered by the Triplet Structure Model. This model has been used with success to teach the conceptual structures of word problems, by allowing young kids to interact with the structure of arithmetic word problems. An experiment has also been done in a local kindergarten. Experiment results show that young kids can also interact successfully with the model.

Keywords: Pre-math, preschool, word problems, arithmetic

1. Introduction

Past research has shown that math proficiency in the early years, such as number sense, can predict math performance in school life (Jordan, 2010). This has been verified all the way to the third year of elementary school. This suggests that building math skills before elementary school can greatly impact how the student deals with math in the coming years. Interventions to teach number sense for both kindergarten and pre-kindergarten students have been done before (Griffin, 2004; Dyson, Jordan, & Glutting, 2013; Starkey, Klein, & Wakeley, 2004; Wilson, Dehaene, Dubois, & Fayol, 2009). These studies focus on whole number understanding. However, these interventions do not focus on word problems which is a big part of how students interact with math after kindergarten. Students will usually encounter word problems in early arithmetic classes in their first year of elementary school. Those word problems describe an addition or a subtraction. Students are often required to:

1. Write the arithmetic expression corresponding to a certain word problem;
2. Calculate the answer by solving the arithmetic expression.

Focusing on the first step, (Rivera, 2014) states that elementary word problems need to be conceptually understood. It states that teachers often teach children to rely on keywords in order to transition to the arithmetic expression. It also states that this keyword-based method shows a lack of conceptual understanding that is necessary for solving harder problems. An analysis by (Hegarty, Mayer, & Monk, 1995) also points out this issue, stating that students that rely on keywords instead of creating a mental model of the problem are usually unsuccessful. Students need to be able to understand the roles of the 3 quantities inside the story. But how to help students develop this conceptual understanding and build the necessary mental model of the problem?

The Triplet Structure Model that will be introduced below attempts to offer a solution by creating a 3 sentence representation bridging the word problem and its arithmetic expression (Hirashima, Yamamoto, & Hayashi, 2014). Monsakun is an interactive learning environment for learning by problem-posing of arithmetic word problems designed based on the triplet structure model. In Monsakun, a learner poses an arithmetic word problem by arranging three sentences cards by selecting three cards from multiple provided sentence cards. Monsakun diagnoses the posed problem based on the triplet structure model and gives feedback. It has been used in elementary schools and it has shown promising results so far, with some experiments suggesting that Monsakun use results in better problem-solving skills, for examples, in forward-thinking addition and subtraction problems (Hirashima, Yokoyama, Okamoto, & Takeuchi, 2007), in reverse thinking addition and subtraction problems (Hirashima & Kurayama, 2011; Yamamoto, Kanbe, Yoshida, Maeda, & Hirashima, 2012) or in multiplication and division problems (Yamamoto, et al., 2014). The problem-posing process has also been analyzed for addition and subtraction problems (Supianto, Hayashi, & Hirashima, 2016; Hasanah, Hayashi, & Hirashima, 2017). These researches reported that affective responses were also positive. Those results suggest that the Triplet Structure Model can be used in the classroom as a way to deepen this conceptual understanding.

Kindergarten students may also be able to learn from the Triplet Structure Model. There is a problem though. Monsakun is based on written sentences. Thus, younger students that aren't used to reading are not in a position to take advantage of Monsakun. So in order to verify if these young students can successfully interact with the model or not, a new application must be developed. This new application must not rely on text in order to provide this interaction.

As for the paper structure, in section 2 we'll clearly state our research questions. In section 3 we'll introduce the Triplet Structure Model. On section 4 we'll introduce our application design and show how it relates to our research questions and to the Triplet Structure Model. In section 5 we show our experiment design and its results. Lastly, on section 6, we conclude our paper by relating our results to our research questions and expanding on further impacts of the results.

2. Research Questions

Our main research question is "Can kindergarten students meaningfully interact with the Triplet Structure model?" In order to answer this, the following questions must be answered:

1. How to design an application for interaction between the kindergarten students and the Triplet Structure Model?
2. Can they use this application? What is their response to the application?
3. Is their understanding and use of the application meaningful and useful? Or are they aimlessly interacting?

To answer the first question, we will show the design of our application and how it relates to the model. To answer the second question, we will run experiments with kindergarten classes and examine their initial response. Afterwards, examining their performance through the application log data will help us answer the third question.

3. The Triplet Structure Model

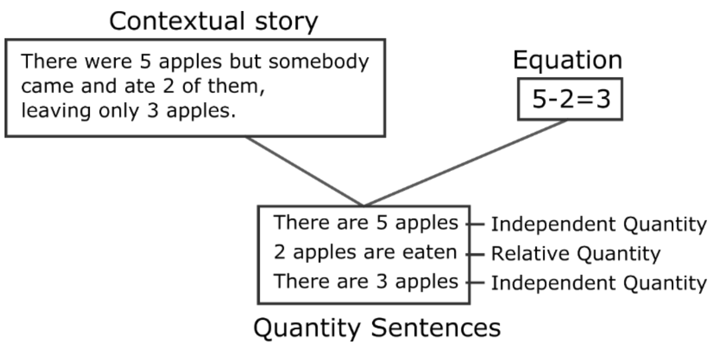

Figure 1 Triplet Structure Model

The triplet structure model is a model that binds the 3 quantities of one arithmetical operation (operand, operant and result quantities) to contextual story roles by using 3 quantity sentences. This is illustrated on Figure 1. It is usually used to describe arithmetic word problems where one of the quantities is unknown.

These quantity sentences can be classified into two types: independent quantity and relative quantity sentences. Independent quantity sentences state the existence of a certain number of objects, such as in the case of "there are two apples". Relative quantity sentences, such as "two apples are eaten" depend on the previous existence of a certain number of objects (two apples cannot have been eaten if apples aren't there), which means that they depend on independent quantity sentences to state that existence.

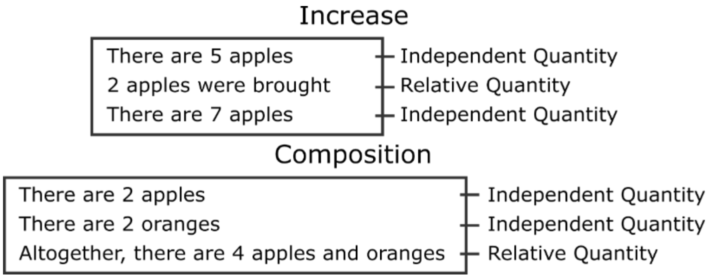

Figure 2 Increase and composition addition stories

The example on Figure 1 contains a case of subtraction, more specifically what the Triplet Structure Model calls a "decrease story". Figure 2 has examples of composition and increase stories, both of those classified as addition stories. Both increase and decrease stories are composed of two independent quantities intercalated by a relative quantity. The relative quantity serves to show how much the amount of the object changed (increased or decreased, depending on the story), while the independent quantities show the amount of objects before and after the change. All 3 quantities in increase and decrease stories must refer to the same object, or else the story is invalid ("there are two apples, one apple is eaten, there is one banana" is not valid, for example).

Composition stories have a slightly different structure. On composition stories the relative quantity comes in the end, with two independent quantities coming before it. The two independent quantities must then refer to different types of objects, while the relative quantity describes the total number of the two objects together. On decrease and increase stories, the relative quantity created a change in the amount of a certain object. In the composition case, the relative quantity it is making a numeric observation about the previous defined quantities without changing their value. Different objects here could be "John's apples" and "Mary's apples", while the relative quantity would be ("John and Mary's apples put together").

There is one more story type that is out of the scope of this paper. It's the comparison story. Due do to the nature of the story, we found it difficult to show it using pictures and decided to not include it in our design. We might include it in future research once we find a satisfactory way of showing it. More information on it and on the Triplet Structure Model can be found in (Hirashima, Yamamoto, & Hayashi, 2014).

4. Application Design

This application must allow for interactivity with the Triplet Structure Model without relying on text. Our solution has been to use pictures and spoken sound. There are two types of pictures. The first one is horizontally large and called overall story pictures. They show the entire problem at once. The second type is the story piece picture. They are small, squared and represent each sentence in the Triplet Structure Model sentence. Understanding the relationship between the overall story pictures and the story piece pictures is similar to understanding how a problem is made up in the Triplet Structure Model. The design of the pictures will be further introduced below. In the application we also ask for users to connect the pictures to numbers. This connection brings them a step further to connect the in-context parts of a problem to the out-of-context parts of an arithmetic expression. This type of connection is in-line with the conceptual understanding of word problems described in previous sections.

We have divided the application activities into levels. Each level has been described below. Level 3, in particular, is critical to the application. It focuses on connecting story piece pictures to big pictures. Performing this requires students to be able to divide the big picture into 3 small parts, each related to a meaningful quantity.

Also worth noting is Level 6 connects the pictures to numbers. At first we ask students to connect story piece pictures to numbers. Since each small picture refers to 1 quantity, connecting 1 meaningful quantity to 1 number is not a hard task. But later the application requests users to connect 1 big picture to 3 numbers. Since no other help is given to the user, he has no choice but to visualize the 3 numbers related to the big picture. This is similar to writing the arithmetic expression of a given problem, but given only the picture of the problem. Students that are able to perform this task well should be apt to meaningfully connecting word problems to their arithmetic expressions.

All of the levels will be explained further below.

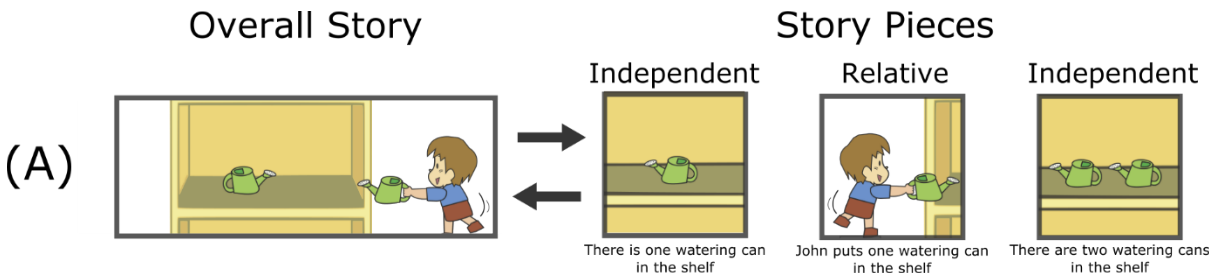

Figure 3 Increase overall story and pieces

4.1 Image and Sound Design in Connection to the Triplet Structure Model

The two picture representations of a Triplet Structure Model story can be seen in Figure 3. Each picture also has an accompanying sound. On the left we have the overall story, where one picture contains all information to describe a story. On the right, we have the story pieces, in which 3 pictures are put together to describe a story.

While on the model we would have "There are 3 apples", in the picture sound we would have "there are 3 apples in the shelf". We describe the place the objects are in to make the connection between what the sound is saying and what the picture is showing stronger.

Story piece pictures come in two types, independent and relative pictures. They are correspondent to independent and relative quantities in the Triplet Structure Model. Independent pictures are usually composed of stationary objects. Relative pictures will usually describe some sort of action, like a boy inserting objects somewhere or an animal entering a place. By describing an action or movement, we can convey the same idea as the relative quantities of the Triplet Structure Model. We can be confident in the children's interpretations of the pictures because very similar designs are used in Japanese textbooks, which are used in Japanese schools.

Overall story pictures represent the entire problem in a single picture. In the overall story picture in Figure 3, the three numbers of the problem can be seen, as

1. the number of watering cans in the shelf;
2. the number of cans the boy puts in the shelf;
3. The total number of cans after the boy inserts them.

So these 3 numbers are mapped to the 3 story piece pictures, creating the relationship between the overall picture and the story pictures. The sound related to the overall picture is a simple combination of the sounds of the 3 story pieces put together. While connecting the overall story to the 3 pictures may seem like a trivial task, it is not so simple. While the first two numbers are quite clear in the overall story picture, the third number, which represents how many cans there will be in the shelf, requires the student to understand the described story and then recognize that there will be two watering cans in the shelf after the boy is done. This number could be calculated by counting or by mental addition, it doesn't matter. What matters is whether or not the student can interpret the story. Since not all quantities are explicitly shown, connecting the overall story picture to the 3 story piece pictures requires more than simply looking at the photo and trying to match the objects or scenery.

4.2 Level 1, Level 2-1 and Level 2-2

On Level 1, participants listen to audio describing a picture and then have to choose, from 3 pictures, which picture corresponds to the audio. In this level, the pictures are story piece pictures and not overall story pictures. This is an introductory stage to introduce the pictures that can make up a story and their corresponding description. Level 2 focuses on connecting overall story pictures to their spoken narration, to ease students into understanding the content of the pictures. It is made up of two parts. Part 2-1 is based on true or false problems, participants hear the spoken narration and are shown one picture. They have to decide if the picture described in the narration is the picture being shown or not. Part two is similar to Level 1, where participants are shown 3 pictures and audio, having to decide which picture corresponds to the audio. Level 1 and 2 work together to introduce the pictures to the user.

4.3 Level 3-1

Level 3 focuses on connecting overall stories pictures to their story piece pictures and it's made up of two parts. On part 3-1, we have true or false problems, with participants being shown one overall story big picture and 3 story piece pictures and then have to decide if the 3 story piece pictures correspond to the same story being shown in the big picture or not, by choosing from true or false buttons.

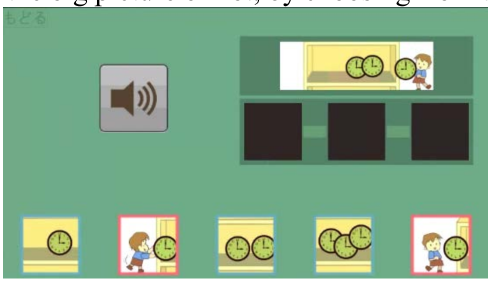

Figure 4 Level 3-2 problem

4.4 Level 3-2

On part 3-2, participants are shown an overall story picture and given multiple story piece pictures. They are asked to use 3 of the story piece pictures to make up a single story. The made up story must correspond to the same story being shown in the overall story picture. Figure 4 shows a screenshot of this setup. Participants are given 5 pictures. Since only 3 pictures make up a story, the remaining two pictures are dummy pictures. Dummy pictures are added to give students more to think about. Problems in Level 3-2 don't all have the same difficulty, the number of blank spaces vary like this:

1. 1 blank: Problem 1 to 5. There is only one blank space. The other two spaces are automatically filled for the player. The player can move 3 of 5 cards.
2. 2 blanks: Problem 6 and 7. Two blank spaces. One space is automatically filled for the player. The player can move 4 of 5 cards.
3. 3 blanks: Problem 8 to 11. All blank spaces are fully opened. The player can move all 5 cards.

This difficulty progression is made up to more easily ease the participants in the workings of how Level 3 and constructing a story from its 3 pieces work. We stress once again that this is a key skill in the context of the Triplet Structure Model.

4.5 Level 4

Level 4 has participants listen to a narration of a story and then they are tasked with forming the story by using story pieces, similar to the second part of Level 3, with the difference being that in Level 3 it was a correspondence with the overall story picture, while on Level 4 it's with spoken narration. It is composed of 8 problems, with the first 3 being easier, only allowing users to move 3 pictures of 5, while the rest of the problems allow the user to move all 5 pictures.

4.6 Level 5

Level 5 shows participants an overall story picture and asks if that story belongs to a certain story type (the types being "increase", "decrease" and "combine"), with the participant having to choose "true" or "false". This Level relates to how well the participant understands the concepts of increasing, decreasing and combining. It also relates to how the participants comprehend the story being show in each picture.

4.7 Level 6

In this Level we have participants connecting numbers to pictures. It is divided into two parts. In part one, students are tasked with connecting numbers to story piece pictures. In part two, students are asked to connect 3 numbers to a single overall story picture, a setup that can be seen in Figure 5. Like stated before, this is a problem that requires deep understanding of the three quantities that can be interpreted from a single picture. Users that are able to do this should be able to construct mental models that allow them to be successful problem solvers.

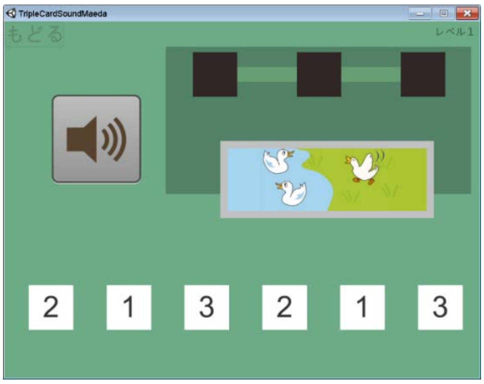

Figure 5 Level 6 problem

5. Experiments

5.1 Experiment Description

The participants of the experiment are 90 Japanese Kindergarten students (around 5 years old), divided into 3 classes averaging 30 students each. A math teacher briefly introduced the application for around 10 minutes, showing the first few problems to the participants by using a projector connected to a tablet. The participants were encouraged to give their opinion on the answer while the teacher advanced through the problems. Afterwards, students had around 20 minutes to interact with the application by themselves, by using an android tablet that contained the application and a headphone. A picture of a kindergarten student interacting with the application can be seen on Figure 6.

Figure 6 A participant interacting with the application

Afterwards, user log data was extracted from the tablets for analysis. Participants measured performance will be compared to their performance if they were "gaming the system". Gaming the system (GTS), in this case, refers to the behavior displayed when students attempt to systematically take advantage of the way the system is made by randomly inputting answers (Baker, et al., 2008). To calculate this performance, we use the probability that students will solve a level in their first try. The probability that students will solve a level on their first try depends on both the level and the difficulty of the problem.

For example, on Level 4, the probability of solving the first three easy problems in one try is 1/3 (only one option with 3 choices). The probability of solving the last 5 problems is 1/60 (5 choices on the first card, 4 choices on the second card, and 3 choices on the third card). "(3 * 1/3 + 5 * 1/60) / 8" gives us the probability of solving every problem in one try on average. We can use a similar logic to calculate the average number of attempts. However, the calculated values are based on which problems the students have done on each level. While uncommon, students could stop midway through a level, restart and complete the level. This means that the calculated values are based on which problems the participants have done for this particular experiment.

A pre-test and post-test was not included in our experiment due to constraints of time in the school's schedule.

Due to a poor choice in the application's implementation, log data was only collected when the user completed a level. The analysis will still be done with the remaining data of the students who completed the levels. This means that our analysis will not include some data from levels that were stopped midway through the level due to time constraints.

5.2 Results and Discussion

Students from all classes were excited about using the application, describing it as fun and stating they wanted to use it more. Students were quick to progress through level 1 and 2 and found difficulty with level 3. We estimate that around 80 students started level 3 and only 13 students have completed it, due to time constraints. This restricts our analysis of later levels to the students who progressed quickly through the system.

Table 1. One sample t-test results comparing measured number of attempts per problem to the equivalent "gaming the system" calculated value. sd stands for standard deviation.

Level	Average N. Attempts	Average N. Attempts (GTS)	T	df	P
1	1.16 (sd=0.45)	2.00	-61.17	1081.00	<0.001
2-1	1.17 (sd=0.45)	1.50	-17.11	549.00	<0.001
2-2	1.24 (sd=0.54)	2.00	-32.82	533.00	<0.001
3-1	1.35 (sd=0.50)	1.50	-2.78	92.00	0.007
3-2	4.77 (sd=9.44)	13.18	-11.05	153.00	<0.001
4	1.54 (sd=1.20)	19.64	-154.41	104.00	<0.001
5	1.23 (sd=0.42)	1.50	-4.27	43.00	<0.001
6	1.31 (sd=1.01)	8.25	-27.35	15.00	<0.001

Table 2.One sample t-test results comparing measured ratio of problems solved in 1 try to the equivalent "gaming the system" calculated value. Data was constant for level 6 so the test was not performed

Level	Ratio of Solved in 1 try	Ratio of solved in 1 try (GTS)	T	df	p
1	0.87 (sd=0.16)	0.33	33.13	99.00	<0.001
2-1	0.84 (sd=0.18)	0.50	18.55	89.00	<0.001
2-2	0.82 (sd=0.18)	0.33	26.11	88.00	<0.001
3-1	0.75 (sd=0.27)	0.50	3.99	18.00	0.001
3-2	0.56 (sd=0.27)	0.21	4.82	13.00	<0.001
4	0.81 (sd=0.24)	0.17	9.43	12.00	<0.001
5	0.81 (sd=0.18)	0.50	5.38	8.00	0.001
6	0.88 (sd=0.00)	0.10	-	-	-

Table 1 and Table 2 compares participants' performance to their calculated GTS counterparts. Measured number of attempts is lower than the number of attempts by gaming the system (GTS). The ratio of problems solved in 1 try is much higher than the equivalent GTS value too. This shows that the strategies students employed to solve each level were more effective than GTS. This suggests that students were not blindly progressing through the application without thinking. Furthermore, this could be indicative that students are displaying the necessary skills to solve each level. It also shows signs that our pictures and their audio description fit with the participants' interpretations of the pictures or else they would not be able to get high scores on the first two levels.

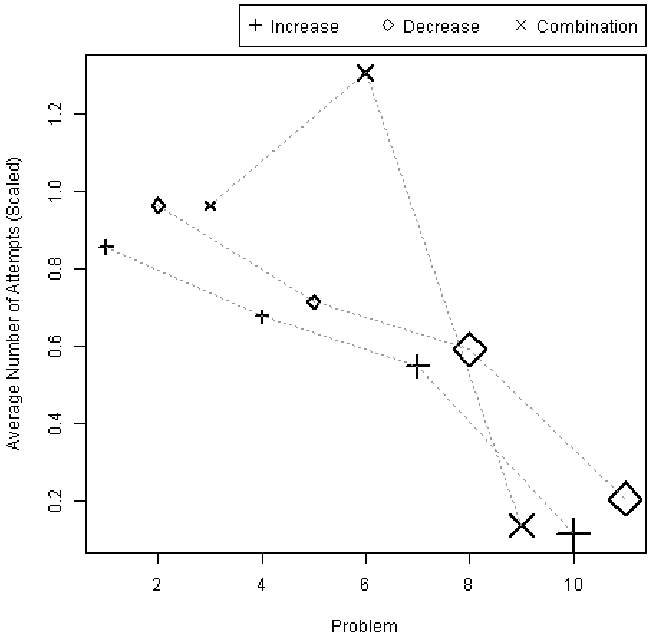

Figure 7. Performance on Level 3-2 problems. The bigger the symbol, the harder the problem. Problem 1 to 5 are the easiest. Problem 6 and 7 are harder. Problem 8 to 11 are the hardest.

Participants' performance on Level 3-2 can be seen in Figure 7. The image shows the number of attempts divided by the calculated number of attempts of each problem during GTS. We divided the value to account for the difference in difficulty between the problems. In the graph, the bigger the symbol, the harder the problem. We can see that participants are clearly becoming more proficient in solving the problems as they advance through the level given the descending tendency in the graph. The spike on problem 6 is when the difficulty first raises. This spike can be attributed to the participants trying to adapt and understand what the task is asking them to do. After problem 6, their overall performance continues to increase, even though difficulty does not go down. The spike on problem 8, when the difficulty goes up again, isn't nearly as sharp as the spike on problem 6, suggesting that after adapting to problem 6 students get a good grasp of what the activity is about.

Let's now look at the problem types separately. Problems 8 and 11 are both "decrease type" problems with the same difficulty, which is the hardest. But the average went from above 15 mistakes to around 5 mistakes. For problems 6 and 9, which are "composition type" problems, the effect is easier to see. Problem 6 (difficulty 2) is easier than 9 (difficulty 3). Despite this difference, students made less mistakes on problem 9. This suggests that past experiences helped the students become better solvers.

Table 3. Comparison between participants who completed Level 6 and the entire group.

Level	L6 kids average N. Attempts	Group average N. Attempts	L6 kids ratio of problems solved in 1 try	Group ratio of problems solved in 1 try
1	1.00 (sd=0.00)	1.16 (sd=0.45)	1.00 (sd=0.00)	0.87 (sd=0.16)
2-1	1.25 (sd=0.45)	1.17 (sd=0.45)	0.75 (sd=0.35)	0.84 (sd=0.18)
2-2	1.00 (sd=0.00)	1.24 (sd=0.54)	1.00 (sd=0.00)	0.82 (sd=0.18)
3-1	1.25 (sd=0.45)	1.35 (sd=0.50)	0.75 (sd=0.35)	0.75 (sd=0.27)
3-2	2.32 (sd=2.34)	4.77 (sd=9.44)	0.59 (sd=0.06)	0.56 (sd=0.27)
4	1.00 (sd=0.00)	1.54 (sd=1.20)	1.00 (sd=0.00)	0.81 (sd=0.24)
5	1.17 (sd=0.39)	1.23 (sd=0.42)	0.83 (sd=0.00)	0.81 (sd=0.18)
6	1.31 (sd=1.01)	1.31 (sd=1.01)	0.88 (sd=0.00)	0.88 (sd=0.00)

Finally, there were two students who completed all the levels. Table 3 compares how the two students performed in relation to the rest of the group. Those two students have shown higher problem solving skills compared to the group. They also performed well in Level 6 itself, solving most of the exercises on their first try. Level 6 involves looking at the overall story in the form of a picture and connecting it with the compounding 3 numbers. As we discussed before, students who perform this well should not have trouble learning to connect a story to an arithmetic expression. The two students' good performance on both Level 3 and on Level 6 fits with our model. In other words, it fits with the idea that being able to divide a story into its 3 quantity concepts is key to meaningfully connect a story to an arithmetic expression. However, little can be said with only two subjects. Further experimenting should shed light into this matter.

6. Conclusion

The use of the application by the kindergarten kids has shown to be satisfactory, both in their affective response and in their performance while solving the problems, which was more efficient than gaming the system. This result suggests that:

1. The application is successful at allowing for meaningful interaction with the Triplet Structure Model without the use of text and arithmetic expressions;
2. The students can meaningfully interact with the Triplet Structure Model through the application.

Furthermore, this suggests that the application design for story problems that relies only on images and sound has been effective. It also shows modest signs that students can interact with the structure in word problems even before starting explicitly studying them in primary school grades.

Unfortunately, students had limited time to interact with the application. This resulted in not enough data being available for the later levels. As we gather more data we will have more compelling evidence that kindergarten students can meaningfully interact with the Triplet Structure Model. Lastly, the two students that have completed Level 6 are likely to have a good grasp of the conceptual quantities in the pictures. These students have also shown remarkable performance while assembling the pictures in Level 3. This shows promising signs of a correlation between the ability to understand the conceptual quantities and the ability to understand the story when divided into 3 parts, which would be suggestive of the effectiveness of the Triplet Structure Model.

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