

Algebra Learning through Digital Gaming in School

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Abstract: Digital games have sparked research interest into how they can be used in school to enhance learning. This study identifies the variation in engagement and learning outcomes when two groups of students use two different digital learning resources for algebra: a game and a web-based resource. Further, the study explores how the digital learning resources create different conditions for social interaction and learning among students and their teacher in a classroom. The setting includes a class of 75 students (age 13–14) in two groups who receive identical instruction from their teacher. Field observations and pretests and posttests show that students playing the game are more engaged, yet their performance on posttests are significantly worse than the other group. Episodes of interaction between participants and technology suggest that they struggle with the symbolic world of the digital game, which constrains the mathematical meaning making that is relevant in schools.

Keywords: Digital games, algebra, mixed methods, engagement, learning outcomes, meaning making

Introduction

Play has been noted by several educational psychologists as important in order for children to construct knowledge and learn (e.g., Piaget, 1951; Vygotsky, 1978). Today, a considerable amount of children's play is dominated by digital gaming on various platforms such as laptops, tablets, and smartphones. Thus, the phenomenon of digital games has sparked research interest in how they can be used in school to enhance learning (e.g., Gee, 2003; Prensky, 2001). This mixed-method study investigates how two digital learning resources for algebra—an award-winning digital algebra game and a web-based learning resource—create different conditions for social interaction and learning among students and with their teacher in a classroom.

Currently, there is no agreed upon definition of what a digital learning game is (Granic, Lobel, & Engels, 2014; Tobias & Fletcher, 2012; Young et al., 2012). Several researchers emphasize that a central aspect in a learning game is that it should be a voluntary activity structured by rules with a defined outcome that facilitates comparisons of in-player performances (Young et al., 2012). However, as others (e.g., Arnseth 2006) have noted, such a notion contains a tension because although game playing usually is voluntary, schooling is not. Thus, because schools are less voluntary, other terms to describe digital learning games have emerged such as “serious games” and “educational games” (Tobias & Fletcher, 2012).

The current debate in game-based learning research focuses mainly on how various types of games or elements from such games can be efficient for learning in classrooms (Tobias & Fletcher, 2012; Young et al., 2012). A meta-analysis provided by Young et al. (2012) indicates that game-based learning can have a positive effect on subjects such as language learning, history, and physical education. However, in the case of mathematics, the results are mixed. According to Young et al. (2012), math games often have a positive effect on engagement but no significant effect on learning outcomes. Nonetheless, there are case studies that show positive effects in terms of learning outcomes in mathematics (e.g., Habgood & Ainsworth, 2011; Kebritchi, Hirumi, & Bai, 2010). More recently, researchers have begun focusing on game-based learning from a social and situated perspective on learning in which the effects are downplayed (e.g., Arnseth, 2006; Silseth, 2012; Young et al., 2012). The argument is that we need to know how students and teachers constitute digital games into learning resources in classrooms, and we need to study how students and teachers interact to make the game meaningful for their specific learning purposes. In this paper, our aim is to contribute to this debate by investigating the following research questions:

- Can we identify any variation in engagement and learning outcome when students use the two digital learning resources—a digital algebra game and a web-based learning resource—for algebra?
- How do the two digital learning resources create different conditions for meaning making and social interaction among students and their teacher in the classroom?

In this paper, we understand learning as socially mediated in and through interpretation and mastery of historical tools and practices (Säljö, 2001; Vygotsky, 1978). Learning is seen as related to the situation that it occurs in, which includes the institutional and historical frames, specifically in the form of formal and informal norms and regulations that exist for the activity. In this perspective, the constructive aspects of learning are

studied, that is, the students' and their teacher's activity and how interactions and utterances are expressions of the participants' meaning making.

Digital gaming in classrooms

As previously noted, meta-analyses of effect studies in game-based learning have found evidence that game-based learning generally has a positive effect on school subjects such as language learning and history (Young et al., 2012). However, in the field of mathematics, the results are mixed (Ke, 2008; Kebritchi et al., 2010; Young et al., 2012). Ke (2008) reports on a mixed methods study examining whether digital learning games, in comparison to traditional paper-and-pencil drills, would be more effective in facilitating learning outcomes in math, and whether alternative classroom goal structures would enhance or reduce the effects of digital games. Ke used eight web-based math games in the ASTRA EAGLE game series during 20 hours over 5 weeks in a summer camp for fourth–fifth graders (age 10–13). Pretests and posttests with a control group show that the students significantly improved their attitudes toward math through gameplay, but there were no significant effects on test performance measured by national test standards. Qualitative data, such as field observations and talk-aloud protocols, revealed several problematic issues, including the pattern of “wandering mouse and random clicking.” This pattern may express guessing and lack of direction. Ke points out that playing a game in itself may promote this usage pattern in order to be fun, but it may not contribute to learning. Ke argues that when designing digital learning games, one might consider integrating goals of gameplay with curriculum goals. A suggestion is to integrate these two aspects in the gameplay in such a way that fantasy depends on the practice of skills, and vice versa.

One approach to integrating goals of gameplay with curriculum goals that has gained support in digital learning games is “stealth learning” (Ke, 2008; Prensky, 2001). In this approach, engagement is emphasized, but formal learning is hidden from the student or player. Through play and engagement, the students take part in productive interactions from a learning perspective but without elements the students affiliate with didactic instruction. One study related to this approach is Habgood and Ainsworth (2011) and their concept of “intrinsic integration” in which they designed a game about fractions in a way that puts the essentials of formal learning content inside the critical parts of the gameplay. Compared to games where formal learning is “extrinsic,” that is, designing the learning elements into the peripheral parts of the game, intrinsic integration is designed to merge fun with formal learning seamlessly and simultaneously. Habgood and Ainsworth's mixed methods study of children (age 7) shows positive results of “intrinsic integration” compared to two control groups, which played the same game but without “intrinsic” versions of the game. A lesson learned from Habgood and Ainsworth's study is that there is a risk of students “staying in the game,” meaning they are unable to break out of the specific condition of the game and cannot apply the knowledge they construct in the game outside game settings. Although Habgood and Ainsworth show positive results, they recognize that it is difficult to bridge actions and what is learned within the game to interactions and procedures normal to a classroom setting. This problem, also noted by Ke (2008), emphasizes the bridging of symbolic interactions within the game with outside interactions such as talking about and solving standard mathematical problems with other resources such as textbooks, paper notebooks, and whiteboards.

Although Ke (2008) and Habgood and Ainsworth (2011) provide us with important information regarding to which degree a game may be considered successful in a classroom context, we still need to understand how the students' and the teacher's understanding of and interactions with a game unfold through hours of gameplay in a school context. Silseth (2012) explores how the computer game “Global Conflicts: Palestine” becomes a learning resource for working with the complexity of the Israeli-Palestinian conflict in school. The aim of his study is to understand how interactions in a gaming context constitute a student's learning trajectory. Silseth applies a dialogic approach to learning, which is an important line within CSCL research, and he observes students at an upper secondary school (age 16–17) for four weeks. By analyzing various interactional episodes, he documents how a student's learning trajectory developed and changed during the project. Silseth's findings suggest that the constitution of a computer game as a learning resource is a collaborative project between students and their teacher. The teacher plays an important role in prompting and guiding the students in various ways to make them collaboratively reflect on their viewpoints and choices made in the game, as well as facilitating the students' adoption of a multiperspective on the conflict. Although Silseth's study is not within the field of mathematics, it is important to note how he goes beyond mere effects of game-based learning to unpack the interactions between students and their teacher and illustrate how the game's function changes over time in a student's learning trajectory.

Our study examines the use of two different digital learning resources, Kikora and DragonBox. The teacher wanted to use these to vary his teaching. This gave the researchers the opportunity to compare the two in terms of engagement and learning, as well as how they create different conditions for meaning making and

social interaction among students and their teacher in the classroom. It is a natural setting and the researchers do not manipulate the classroom practices in this study. We will now briefly describe Kikora and DragonBox with an emphasis on what is most relevant for our study.

Kikora

Kikora is a web-based learning resource in which problem solving in algebra is close to the current practice in schools. Kikora follows largely the course found in standard textbooks, with the presentation of tasks and structures to solve them. The students are presented one task at a time. To answer the tasks, they use a specialized panel that may resemble buttons on a calculator with the basic arithmetic operators as well as square root, exponent, parentheses, and more (Figure 1).

When submitting an answer, the students get immediate feedback. This also applies to intermediate steps in the calculation as they enter the answers to such steps. By clicking a button, the students can ask for a hint for the next step in the calculation or the whole process of solving a problem. A correct submitted answer (or intermediate step) results in a green check mark, whereas an incorrect answer results in a red 'x'. When finishing a subchapter within a mathematical theme, they receive congratulations, and when finishing a theme, they get a "trophy".

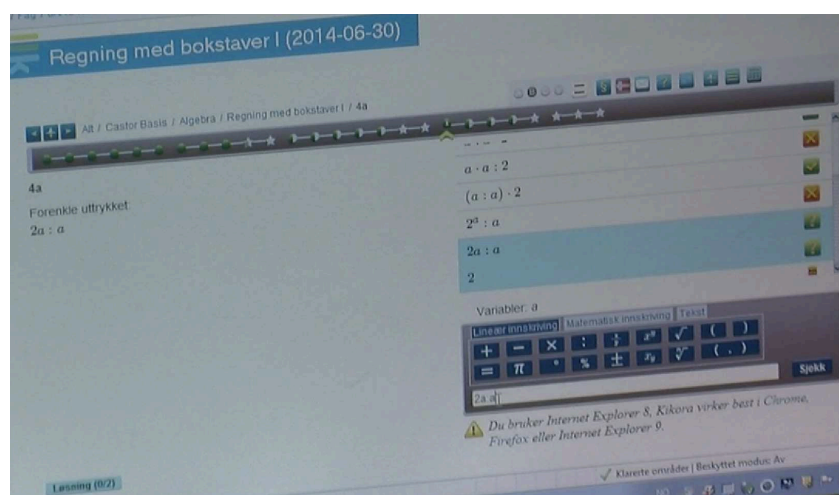


Figure 1. A screenshot of Kikora. The task is in the upper-left corner, and the 'hint' button is in the lower-left corner. The intermediate steps are shown above the specialized panel on the right.

DragonBox (Algebra 12+)

DragonBox is an award-winning game about algebra. In the game, running on tablets, students can manipulate elements in an equation through specific rules. The rules change slightly during the game depending on the students' progress. As they progress, the equations become more advanced, and new rules are introduced and visualized as new capabilities for interaction. The symbols also develop from figurative to more mathematical. In the beginning of the game, the symbols look like fish, insects, or dice (Figure 2); at the end of the game, there are equations with x , constants, numbers, and mathematical symbols.

The game consists of two large fields corresponding to the two sides of an equation, along with a storage located underneath consisting of objects that can be pulled out and placed within the two fields. The game is organized into chapters with increasing difficulty. A level ends when the main symbol—the dragon box (and later an " x ")—stands alone in one field. Other evaluation criteria are whether the player has used the correct number of steps and whether there is an excessive number of objects in the other field that could have been eliminated. The player gets feedback on whether the criteria for successfully solving a level are met by getting one, two, or three stars.

An object can be moved into a field and inside an equation in accordance with the four basic arithmetic operations. It may add to or subtract from a side in the equation depending on how the student has assigned a plus or a minus sign to the object in the store, act as a multiplier when placed beside another object in a field, and act as a divisor when it is placed beneath an object and thus creates a fraction bar or a multiplication of an existing divisor.

When an object is drawn into a field, algorithmic rules are activated. When the player adds or subtracts an object on a field (one side of the equation), a dent appears in the other field (the other side of the equation),

which shows that a corresponding object should be placed there. The student cannot progress further in the game until the dent has been filled with a corresponding object.

In terms of game-based learning in school, Kikora and DragonBox represent two different approaches. Although Kikora offers rewards, it is close to standard algebraic notation and practices for problem solving found in textbooks. DragonBox offers a different approach to algebra compared to textbooks and Kikora. The aspect of gameplay in DragonBox is evident, and it can be seen as an example of stealth learning (Ke, 2008; Prensky, 2001) because some of the known difficulties of algebra are deliberately hidden. The students are presented with algebraic rules but mainly through direct manipulation of nonmathematical symbols. Through a point system and levels, the game gradually moves toward more standardized mathematical symbols. The students also participate in this “translation” through gameplay, and potentially they will see the rules and symbols as expressions for algebra.

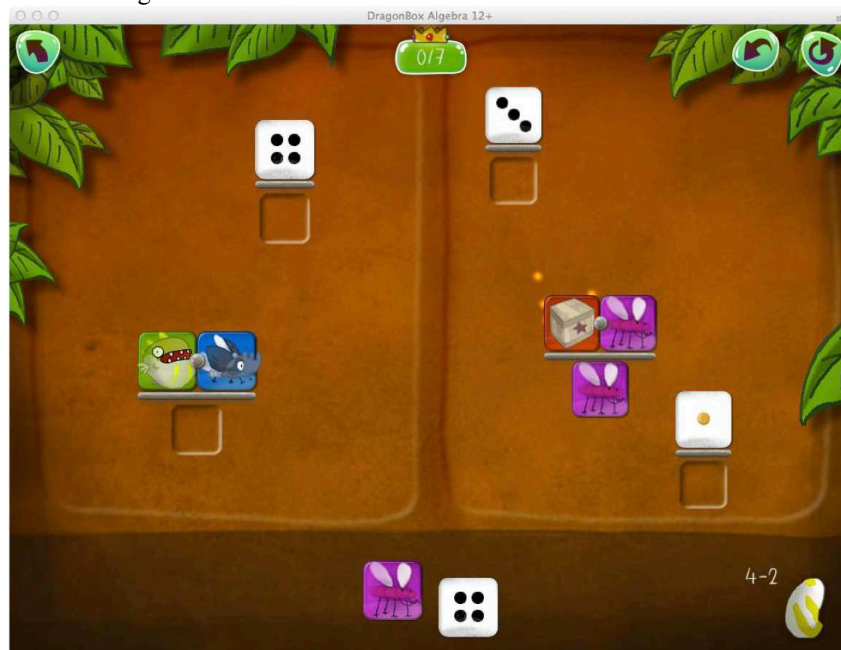


Figure 2. A screenshot of DragonBox.

Method and setting

We observed a class of 75 students in eighth grade (age 13–14) who worked with algebra through a 4-week period (total of 8 clock hours). The class of 75 students was divided in two; one group used DragonBox in their group, and the other used Kikora. A pretest and a posttest just before and after the trial documented the students’ performances in algebra. We conducted a video observation of whole class instruction and of four pairs of students (two pairs in each group), which were followed throughout the process. About half of the time was spent on plenary teaching, and the rest of the time was spent on work in pairs with the digital learning resources. The plenary teaching for the two groups was conducted by the same teacher and was virtually identical. The identical arrangement between the two groups of the class provided opportunities to examine the different conditions and outcomes provided by the use of the two digital learning resources, Kikora and DragonBox.

Our fieldwork resulted in about 25 hours of video material, where about 12 hours related to plenary sessions and about 10 hours showed students working in pairs with either Kikora or DragonBox. We also did interviews with eight students and the teacher, which resulted in about 3 hours of video material. By analyzing field observations, field notes, and video material (Derry et al., 2010), we looked for similarities and variations that emerged from the tests. We identified typical examples of conversations and activities in the interactions between pairs of students, with their teacher, and with the technology. Two examples are presented below. Detailed qualitative analysis of the activities and conversations related to the identified variations found in performance of the tests may give researchers a robust understanding of how the technologies create different conditions for meaning making and social interaction among students and their teacher in the classroom (Dolonen & Ludvigsen, 2012).

Results

Pretests and posttests

To find a variation of learning outcomes during the process, we carried out a test before students began their algebra course and a similar test afterward. The tests were developed with the teacher and were based on the national curriculum targets, the textbook, and TIMSS items (the latter as identified by Naalsund, 2012). The pretest showed negligible differences between the two groups of the class. Each of the 8 questions gave 0–2 points so that the maximum of possible points was 16.

Table 1: Results from Pretests and Posttests

	Pretest Mean Scores (standard deviation)	Posttest Mean Scores (standard deviation)	Mean Performance Increase
Kikora group	5.17 (2.01)	9.91 (2.43)	4.74
DragonBox group	5.21 (3.36)	7.76 (3.66)	2.55

As Table 1 shows, there was a relatively large variation in performance between the group of students who worked in pairs using Kikora and the group of students who worked in pairs using DragonBox. Using a paired t-test for each group, the variations in performance from pretest to posttest are statistically significant ($p < 0.01$) for both. Using an independent t-test on the variation in performance between the two groups on posttests only is also statistically significant ($p < 0.01$). The teacher and one researcher did the scoring with an inter-rater reliability score of 0.918 using Fleiss's kappa (95.4% pairwise agreement). Thus, we can argue that both groups showed significant performance increase from pretest to posttest, but that the Kikora group increased significantly more than the DragonBox group.

To give an example of this variation, question 2 in the tests instructed the students to write the expression $3x + 2x + 6x$ (in pretest) and $2x + 3x + 8x$ (in posttest) as simply as possible. Related to this question, the mean improvement in performance for the DragonBox group was 18 percentage points (from 12% to 30% of maximum value), while Kikora students had a mean improvement in performance of 51 percentage points (from 20% to 71% of maximum value).

The significant variation in performance on the tests was surprising to us for three reasons. First, both groups spent 4 hours in plenary sessions in the 8-hour course with the same teacher and identical teaching. Second, we observe that students who used DragonBox expressed far more engagement along the way by enthusiastic discussions with each other as well as intensity in usage patterns. Observations of gameplay show that in DragonBox the students do not have to write expressions in order to solve equations. The students have a storage with a limited amount of appealing objects that fast and easily can be dragged and dropped unto and within the game board. In contrast, to solve an equation in Kikora the students have to write an expression with formal math symbols in a calculator, and check if the answer is correct. If the answer incorrect the students must rewrite the expression in the panel. As a result, the DragonBox group also spent more time using the learning resource by being far less distracted and doing off-task interactions than the Kikora students did. Third, the technology was timely beneficial for the DragonBox group because they worked on tablets while the Kikora group used laptops. The tablets were faster to start up than laptops, where much time was spent on plugging the machines in, starting them up, and getting them connected to the Internet. Easier startup gave the DragonBox students working in pairs almost an hour (58 minutes) more time on task compared to the Kikora students working in pairs. These reasons made us analyze what happened in the process between the two tests, and we focused on situations where students worked in pairs with the learning resources.

Interactions when using Kikora and DragonBox

From observations and video material from the plenary sessions and video of selected pairs of students, we analyzed the processes of student interactions in the algebra course. In general, we observed that the work in pairs was goal directed in both groups, and transcripts of the video recordings show that students discussed with each other and their teacher, and such discussions were aimed at both problem solving and technology use. However, the students and their teacher show variations in talk and interaction when using Kikora and DragonBox. We will now present short excerpts, one from a pair using Kikora and another from a pair using DragonBox. They are selected as typical examples of interaction between students working in pairs and their teacher when discussing mathematical concepts using their digital learning resources. In the first excerpt, we observe the two girls, Irene and Anne, trying to simplify the fraction $2a / a$ in Kikora. The teacher who walks around guiding pairs has just arrived at their desk:

1. Irene: Uhm... If we take ... 2
2. Anne: Raised by...
3. Irene: 2...
4. Anne: Isn't that... a? *(They get the wrong answer.)*
5. Irene: No. That was wrong. *(Here they click the "hint" button in Kikora and get the answer: 2.)*
- (...)
6. Irene: Only 2?
7. Teacher: Mmm. *(confirming)*
8. Anne: Yes, but how can that be correct?
9. Teacher: You can... If you set it up... You could use the paper notebook.
10. Anne: We have it.
11. Teacher: If you use a fraction bar, then you can write it as "2a" and then the fraction bar and then the "a" underneath it. Agree?
12. Anne: Yes.
13. Teacher: Mmm *(confirming)*. If you have the paper notebook...
14. Anne: Yes that's correct but... *(opens her paper notebook)*
15. Irene: *(With the keyboard looking at the teacher)* Ok, now I've written...
16. Teacher: *(Addressing Anne and her paper notebook)*. Now, it is possible to shorten a bit when you are dealing with fractions.

This excerpt starts with the students using an exponent to solve the fraction. Having requested a response from Kikora, they are quick to conclude that using an exponent is not correct (line 5). The unexpected answer challenges them (lines 6 and 8), and the teacher recommends that they use the tools they know—paper and pencil—and calculate using a paper notebook (lines 9 and 13). He guides them through the work of setting up the fraction, refers to shortening fractions as a method (and a concept) (line 16), and since they already have the solution given by Kikora, they eventually find the procedure to correctly solve the problem.

By setting up the fraction with a traditional fraction bar and mentioning the concept of shortening a fraction, the teacher provides the students with tools that are close to a repertoire of problem solving they already know. The teacher attempts to bridge the representation of the problem in Kikora and how it can be represented and processed using a paper notebook. Thus, the teacher is able to guide them in the right direction by using multiple representations that are close to the students' cultural and historical practices. The episode indicates that the total picture of guidance by a teacher using concepts and standard notation in algebra through culturally well-known aids such as paper notebooks together with Kikora showing the answer provides a developmental zone that brings the student from an incorrect procedure using exponents to an understanding of the method that will produce the correct answer. We observed this repeatedly for pairs using Kikora.

Now, let's turn the attention to an excerpt in which students use DragonBox. It exemplifies what we observed when students used the game in the classroom. In the excerpt, the students try to solve an equation in which the dragon box (representing the unknown in standard algebra) is under a fraction bar in the right-hand field by eliminating a black fish symbol above the fraction bar. When a white fish symbol is dragged from the store and laid on the black fish symbol, it is eliminated and turns into a dice with one dot (representing the number 1).

1. Teacher: Remember what you did when you wanted to, in a way, move and change *(points at the symbols in the expression in the right field)* to make things appear in other places.
2. Ellie: Yes but... When we do it becomes like a circle or a dot.
3. Lilly: Dice.
4. Ellie: Dice, yes, with one dot.
5. Teacher: Mmm. *(confirming)*
6. Ellie: And then there appears another one. *(It is the mechanism that shows that they had to add a similar dice to the left field in order to balance the equation.)*
7. Teacher: Yes.

8. Ellie: And then it won't go away.
9. Teacher: No.
10. Ellie: No. *(both girls laugh)* Uhm...
11. Lilly: Should we just try something like this then? *(The girls try to move some symbols from the storage to both fields, but they seem helpless.)*

In this episode, the teacher tries to apply a mathematical concept in algebra that he knows the students know (line 1: “move and change” is a local concept for changing the sign of an integer when moving it from one side of the equation to the other). Later, however, neither he nor the students use standard math concepts such as fraction bars or numbers as we observed when using Kikora. For example, they do not talk about “the sides of the equation” that must be subjected to the same operations, which are relevant here. DragonBox has a symbolic language and problem-solving methods that represent a new world of mathematics for students and teachers. This mathematical world transforms gradually into more formal symbols and methods, as we know them from standard textbooks. The variety of symbols and methods for each task and each level makes it difficult for students and their teacher to be precise in their use of concepts when talking math. The teacher utters “things” (line 1), the students “like a circle” (line 2: a circle looking like a portal represents the 0 symbol in the game often used in addition and subtraction), “dot” (line 2), and “dice” (line 3). Eventually, we see that the teacher goes over to short utterances such as “Yes” or “No” (lines 5, 7, and 9), suggesting that he struggles to create a developmental zone for the pair. The field observations we made also suggest that some of the students, but not all, enter into a game-like mode characterized by unreflected trial and error. The students and their teacher do not use established practices in mathematics when they use DragonBox. The excerpt, which was representative of how the teacher guided students working in pairs, suggests that this symbolic world is difficult to talk about conceptually and is not easily transferred to paper notebooks or the whiteboard.

Discussion

Our aim with this mixed-method study is to contribute to the research and debate on game-based learning in classrooms. Our first research question concerns whether we can identify any variation in engagement and learning outcome when students use the two digital learning resources for algebra: a digital algebra game (DragonBox) and a web-based learning resource (Kikora). Our results show that there were obvious variations in student engagement and the results achieved using DragonBox and Kikora. The pairs using DragonBox showed a high degree of involvement and enthusiasm, almost continuously. It is rare to observe in mathematics classrooms that all students remain focused throughout the school hour and even in some cases want to work on longer. In contrast, the use of Kikora was not very different from ordinary problem solving in mathematics classrooms with paper and pencil, and it did not create any particular engagement or enthusiasm. Thus, it is surprising that the variation in learning outcomes as measured in tests was strongly and significantly in favor of pairs working with Kikora, although they were far less engaged and used less time on tasks.

Our second research question concerns how the two digital learning resources create different conditions for meaning making and social interaction among students and their teacher in the classroom. In this study, we observe how Kikora and DragonBox made possible but also constrained the interactions among students, their teacher, and the technology. The symbols and methods of problem solving applied in DragonBox did not support students and their teacher in terms of the formal language that exists for algebra, which is what is tested at school. Both the students and their teacher struggled to apply their repertoire for mathematical language using DragonBox, thus the teacher was unable to orchestrate a developmental zone between the students' existing knowledge and concepts and forms of symbolic interactions in DragonBox. Instead, the students' problem-solving were characterized by trial and error, indicating guessing and lack of direction. In Kikora, however, the teacher could apply a well-known mathematical language and a repertoire for helping students when they were struggling, but the learning resource did not add much compared to regular exercises in algebra.

This study has both practical and theoretical implications. In terms of practice, this study highlights the debate about the possibilities for using games in schools. The challenge is to design games that not only make students better at playing games but that also may be included in a school context and promote school-relevant learning. One aspect is that there is an inherent tension between the voluntary element of gaming and the involuntary element related to school. Another aspect is that the introduction of new games with novel symbolic worlds can create practical problems for teachers wanting to guide their students into algebra. It takes time to master a novel symbolic world and make it relevant in a school context. Theoretically, this study does not strengthen the DragonBox approach to algebra learning, which can be categorized as stealth learning (Habgood & Ainsworth, 2011; Ke, 2008; Prensky, 2001). The game provides engagement, but the results suggest that

symbolic interaction in the game constrains the participants' use of a well-known mathematical repertoire. Although students potentially learn a practice in and through DragonBox, it does not fit in terms of the school's practice of algebra. Further, this study also shows how important it is to go beyond reporting statistical effects of a practice. When we analyze the interaction of the participants, we may observe the aspects that create opportunities and constraints when participants try to make meaning out of technology and make it relevant for the context they are in (Silseth, 2012).

To conclude, this study addresses the debate and research of games in schools. It has been argued that it is important for the teacher to be able to bridge the gap between engagement in gameplay and curriculum goals (e.g., Habgood & Ainsworth, 2011; Young et al., 2012). However, to do so, it is important to understand that a game and a school are potentially two different activity systems, often with different symbolic interactions and purposes, which make it challenging for students and teachers to make meaning out of the game that is relevant to the school's norms for what it takes to know a discipline.

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