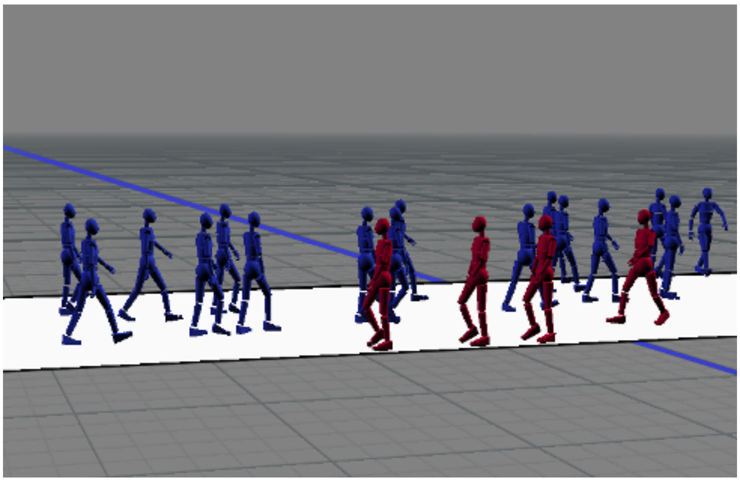
Using simulations to stimulate higher-order thinking in the solving complex problems



Abstract

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Abstract

This study investigates how simulation in the classroom can be used to stimulate and improve critical thinking, also known as higher-order thinking. It uses simulation and is based on a mixed strategy of problem-based learning and problem-posing education. To ensure that the simulation could be used as efficiently and effectively as possible, additional use was made of self-developed instructions and questions via video and worksheets. The research was conducted at a pre-university school among students, both singles and duos from the first year. Because both the approach of singles and duos was examined, the difference between them could also be studied. The results are categorized using Blooms' taxonomy. This study demonstrates that with the chosen approach the students are challenged to the use of higher-order thinking. In addition, the students without exception found this a stimulating way of working and learning.

Key concept / frameworks

Critical thinking, Problem Based Learning, problem-posing education, simulation.

Introduction

In our current society students' critical thinking skills are not developed enough. For instance, Wilson (2019) states: ".. students are poorly prepared, as they have spent their early undergraduate years' operating in a positivist paradigm of passive learning, never truly challenging the learning material." This is a problem because whatever we do, the ability to think clearly and rationally is important. Being able to think well and to solve problems systematically is an asset for everyone. Some of the present students are the next generation of global leaders. We need leaders that can think critically and solve problems. The proper functioning of a liberal democracy requires citizens who can reflect critically on social issues and form a weighted judgment on good governance. More critical-thinking abilities are therefore needed in our society. "People who think critically consistently attempt to live rationally, reasonably, empathically." (Elder, 1996). This sets a task for education to support the development of critical thinking skills throughout students' educational career.

Critical thinking refers to the ability to analyse information objectively and make reasoned judgments. A nice way to practice critical thinking is the Problem Based Learning (PBL) strategy. Based on the conceptual definition of Bailin et al (1999) PBL possible nurtures critical thinking ability (Masek & Yamin, 2011), through the process of problem-solving. It is believed that probing questions may engage students in a systematic cognitive process that promotes the development of the students' critical thinking. PBL challenges students to solve real-world problems and develop solutions. The students have to make their own decisions, develop their own hypothesis and be critical about their findings.

PBL stimulates searching for the solutions of problems by systematic generating and testing of solutions. This relates to the work by Papert (1993), the so-called trial-and-error behaviour. By letting the students discover and apply solutions themselves, the creativity of children at this age is exploited. Through trial and error, children learn that failure is part of life and that there often are no unambiguous answers to complex questions. It supports the natural playful behaviour of children and this builds their self-confidence and confidence promotes critical thinking. Trial-and-error is trying and learning from mistakes. It is this behaviour that ensures that good experiences stick and bad experiences are no longer used. The conclusion of an extensive review by Masek and Yamin (2011) on the effect of PBL on critical thinking is, that

PBL supports critical thinking if the curriculum carefully is designed to enhanced PBLs' effectiveness. This, according to Masek and Yamin, includes the role of a facilitator in mediating students learning, particularly in triggering students' metacognitive thinking. Masek and Yamins' conclusion ensured that in this study besides the use of PBL a facilitator was chosen to guide the students into critical thinking.

In this study, computer simulation is exploited as facilitator for the support of critical thinking. Simulation is highly appropriate for proposing real-world problems and giving students handles to develop and test solutions. Also, the properties of simulation contribute to a great extend to trial-and-error behaviour. The limiting factor was during the sessions, there was not enough time to try all kinds of solutions. Therefore, through explicit guidance, the students were kept on the path to the ultimate goal. So as additional guidance instructions and questions were developed. These were given via instruction videos, a symbol sheet and a worksheet. The aim of the current study was to investigate whether students' critical thinking skills can be enhanced by implementing a PBL environment including simulation as facilitator.

Theoretical background

Critical Thinking (CT)

Several authors have provided definitions for CT. Examples according to Finley are (2014):

- "Seeing both sides of an issue." Willingham (2008).

- "An ability to use reason to move beyond the acquisition of facts to uncover deep meaning." Weissberg (2013)
- "A reflective and reasonable thought process embodying depth, accuracy, and astute judgment to determine the merit of a decision, an object, or a theory." Alwehaibi (2012)
- "Self-guided, self-disciplined thinking which attempts to reason at the highest level of quality in a fair-minded way." Elder (1996)

Critical thinking is difficult to teach because it is an abstract conceptual skill and there is no standard model on how to think critically. Critical thinking is in the family of higher-order thinking skills, along with creative thinking, problem solving, and decision making (Facione, 1990). Critical and creative thinking are connected to each other, in producing effective thinking and problem solving (Treffinger et al., 2006). These skills can be enhanced by devising instructional methods that stimulate higher-order thinking in theory and practice (Facione, 1990). Evidence suggests that the complex cognitive skills can be systematically taught (Jianzeng et al., 1997). For that reason, teaching higher-order cognitive abilities such as critical thinking has always been the ultimate goal of education (Spendlove, 2008).

Problem Based Learning (PBL)

Problem Based Learning (PBL) is chosen as the strategy for this study. According to Masek and Yamin PBL is often theorized to promote students' higher-order thinking skills, such as critical thinking. PBL is anchored by students-centred learning approach that follows constructivist learning theory principles (Hmelo-Silver, 2004). In this context, knowledge acquisition becomes one of the prerequisites in developing students' critical thinking ability (Hmelo-Silver, 2004; Winterton et al., 2006). According to Winterton et al. knowledge and working memory play major roles in the acquisition of complex cognitive skills. This is especially true because knowledge is operational and works within a social and attitude environment. Ennis et al., (2005) indicate that critical thinking is a reflective thinking that focuses on deciding what to reasonably believe or do. It is an analytical process to arrive at a logical, rational and reasonable problem-solving (Bailin et al., 1999; Facione, 2006).

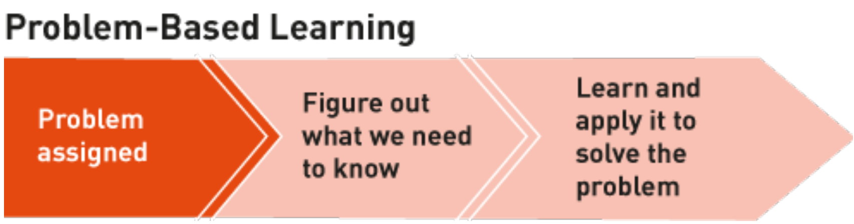

Figure 1: Problem Based Learning (by Researchgate)

As referred before the critical thinking ability is possibly nurtured by PBL (Masek & Yamin, 2011), through the process of problem-solving. In addition, other processes, such as discussion, debating, sharing, and teaching one another, creates a platform for students to experience an environment that is conductive for critical thinking to grow (Wee, 2004). Similarly, students develop their critical thinking, especially reasoning skills through the process of interaction, reflection, and feedback in the problem-solving or in the formative assessment process (Savery & Duffy, 2001). Within this capacity, a strong basis exists that supports PBL's contribution to students' higher-order thinking skills, especially critical thinking ability. Regarding the reasons mentioned above PBL seems to provide an appropriate strategy to enhance critical thinking skills. However, in an extensive review of Masek and Yamin (2011) on the effect of PBL on critical thinking it is conclude that there many PBL research that resulted with unexpected findings, leading to a conflict on the effect of PBL on students' critical thinking ability, The overall conclusion of Masek and Yamin is: "The implication is that, Problem Based Learning (PBL) curriculum must carefully be designed and concerned on the critical elements contributing to PBL effectiveness. This includes the role of a facilitator in mediating students learning, particularly in triggering students' metacognitive thinking. With all these carefully considered, PBL may successful as what has been noted in the theory.". This conclusion, together with Hmelo-Silvers' concluded that a facilitator stimulates students' critical thinking in looking for a best solution, which is also in light with the concept of scaffolding from the Constructivist Learning Theory (Hmelo-Silver, 2004; Wee, 2004), started me thinking about using a type of facilitator to guide the students into enhanced critical thinking.

Trial and error

Papert (1993) promoted Trial-and-error behaviour in learning. Students apply a solution, see that it is not yet what it should be, analyse the given solution and adjust the solution. As a result, students have to exit their comfort zone, but remain in a safe environment in which they are in control.

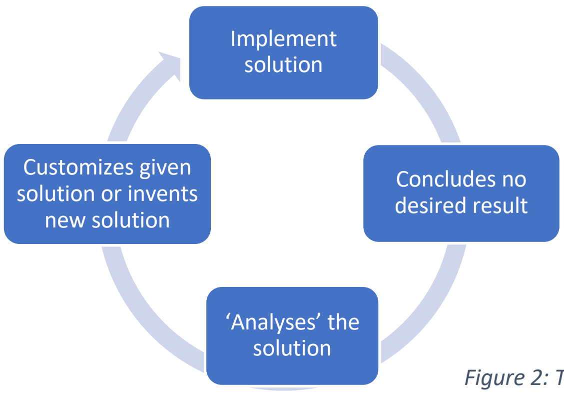

Figure 2: Trial-and-error behaviour

Young children are playful and inquisitive. And it is precisely this behaviour that makes young children always want to try something different in order to arrive at a good solution. Older children are often less inquisitive, more insecure, don't dare to try, think they can't do it (Papert, 1993).

Problem-posing education

In research of improving critical thinking problem-posing education is a term coined by Brazilian educators Freire and Ramos (1970) in their book Pedagogy of the Oppressed. Problem-posing refers to a method of teaching that emphasizes critical thinking for the purpose of liberation. It has been found that problem-posing activities can improve students' thinking and create more learning opportunities for students at different levels.

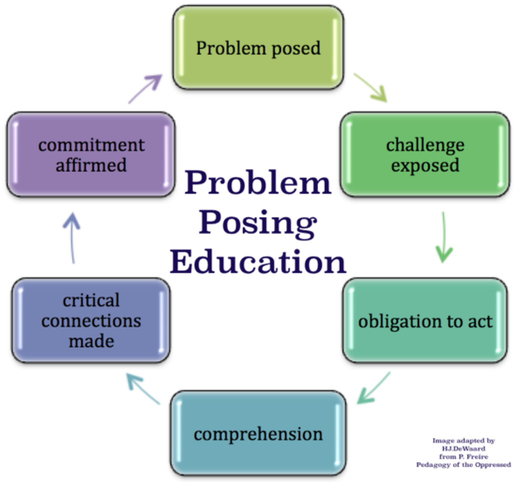

Figure 3: Problem posing education

Leung (1993) created four phases of problem-posing: problem-posing, planning, problem-solving, and looking back. She found that the problem-posing activities helped students solve problems that they generated by themselves. When solving their own posed problems, they performed solutions and looked back at the process. They then revised their own posed problems and generated new ones. Through the process of problem-posing, students could clarify and enhance their understanding of the concepts of the subject matter and subsequently enhance their critical thinking (Chang et al., 2012). It therefore seemed that problem-posing activities appear to be adequate to be used in this study.

With the rapid advancements in information technology and the discovery of the boosting effect of problem-posing on problem-solving abilities and motivation in learning, researchers have attempted to develop problem-posing systems by applying information technology (Chang et al., 2012). Chang et al. proposed a problem-posing system with the forementioned four phases: posing problem, planning, solving problem, and looking back. Simulation can be used as such a system.

Using simulation

Wilensky et al (2015) described a change in the representational infrastructure of how knowledge is externally expressed in a domain which affects how knowledge is internally encoded in the mind. Wilensky's NetLogo is a multi-agent modelling language. NetLogo is designed to enable students to explore and construct models. By exploring and constructing such models, students make connections between the micro-level of agents following rules and the macro-level patterns and regularities that constitute the world of natural and social phenomena. This is a powerful idea for the design of learning environments because just as algebra made Galileo's difficult concepts more accessible to the public hundreds of years ago, restructuration's, particularly those involving computational tools, can make complex concepts more accessible to students today. Computational tools could help as connection to the thinking ability and perception of the students.

A computer simulation is such an attempt to model a real-life or hypothetical situation on a computer so that it can be studied to see how the system works. By changing variables in the simulation, predictions may be made about the behaviour of the system. It is a tool to virtually investigate the behaviour of the system under study (Banks et al., 2001). Support for this is also the research by Rutten et al. (2012) in which the application of computer simulations was compared with traditional instruction and were it seemed to indicate that traditional instruction can be successfully enhanced by using computer simulations. Also, it seemed that improvements of learning outcomes by fostering a sense of immersion are better supported by mixed-reality learning environment that integrates computer-generated data with real-world components. (Rutten et al., 2012). The effects of simulation and integrated curriculum designs such as PBL courses on student critical thinking, problem-solving abilities and learning were appraised by Kim et al. (2012) and Son and Song (2012). Simulation seems therefore an adequate tool for problem-posing activities. In the aforementioned research of Chang et al., the solving problem phase can be implemented by simulation scenarios to support students in the process of problem-posing, allowing them to fully engage in the problem-posing activities.
Computer games as educational tools are also suggested as an intrinsic motivational factor that stimulates curiosity and allows students to maintain control over their own learning process (Dickey, 2007, Huizenga et al., 2009). Lovelace et al. (2016) found that participation in the simulations was an effective way to develop critical thinking skills. Important point of consideration according to Goodstone et al. (2013) suggested that not the simulation itself but use of a correct instructional design is important.

Point of interest also according to Windschitl and Andre (1998) was that reducing the use of computer simulations to a step-by-step cookbook approach undermines their potential to afford students with an opportunity to freely create, test and evaluate their own hypotheses in a more richly contextualized environment (Windschitl & Andre, 1998). It was therefore important that the students continued to feel that they were free to come up with their own solutions.

Using simulation as facilitator

It was the intention that the students were guided by a simulation mechanism towards higher-order thinking. First of all, the simulation tool was studied extensively to see how it could be used in the wanted process of problem-solving, necessary to promote the development of the critical thinking (Masek & Yamin, 2011). It was desired to translate common problems into challenging problem-posing activities. The strategy was that the students would first think about a possible solution, and then write this solution down, following Quinn and Alessi (1994), who forced their students to write down, before experimenting, a single most plausible hypothesis or a list of multiple plausible hypotheses. The idea is that having more hypotheses available will lead to a strategy of elimination, which could be better than focusing on one hypothesis at all. After writing down the hypothesis it was the intention that the students applied their chosen solution in the simulation themselves, so that they could immediately see the effect of their solution, allowing them to analyse and evaluate the operation of their chosen solution, and possibly adapt it. Originally, it was the idea to modify the simulation tool so that it could work independently as a facilitator for this entire route. This was not possible because there was a lack of manpower to adjust the chosen tool. The solution was that four simulations were developed and that the explanation of the outlined problem and guidance of the application, analysis and evaluation of the solution were done by additional instructions and questions via video and accompanying worksheet. In this way, together with the instructions and appropriate questions the developed simulations acted as the facilitator.

The structure of this study is partly based on Friedler, Nachmias, and Linns' structure: (a) define a scientific problem; (b) state a hypothesis; (c) design an experiment; (d) observe, collect, analyse, and interpret data; (e) apply the results; and (f) make predictions on the basis of the results (Friedler, Nachmias, and Linn (1990)).

SimCrowds

This study was done by using simulation as a tool. The simulation will function as an interface with which problems are described and with which the student can solve these described problems.

The used simulation tool is SimCrowds (Simulation Crowds), developed by the Utrecht University spinoff uCrowds. This simulation models intelligent pedestrians with unique properties that route with activity-based routing. The pedestrians can react on triggers and a dynamically changing environment. It offers five different movement levels of the crowd, realistic collision-avoidance, social group behaviours, instant updates of the global routes and local paths when an obstacle is added, deleted or moved, real-time simulation of 50,000 people, and more.

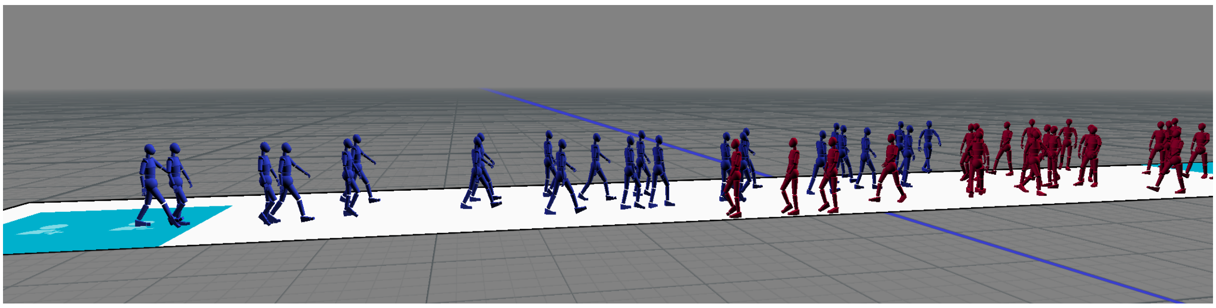

Figure 4: Example of the use of SimCrowds

SimCrowds offers the student a secure environment in which to safely test their own thoughts and ideas.

Operationalising by using Blooms' taxonomy

To gain insight whether the behaviour shown demonstrates that the use of critical thinking can be amplified by simulation, the learning taxonomy of Bloom ((Bloom et al, 1956) is used. This framework begins with the stages remembering and understanding. These skills of thinking are an important foundation for moving our brains to higher-order levels of thinking. These higher-order levels are needed for problem-solving and critical thinking. To describe critical thinking Bloom's learning taxonomy of educational objectives uses the phrase "intellectual abilities and skills". In Bloom's version these stages are: analyse, synthesize and evaluate. These so-called "higher-order thinking skills" are critical thinking skills. Bloom's learning taxonomy is studied by Miller et at (2010) to assess what kind of simulation stimulates which learning stages. This present study uses the revised version of Bloom's learning taxonomy by Anderson & Krathwohl (2001). The revised version treats critical thinking as cutting across those types of cognitive process that involve more than remembering and understanding. Anderson et al (2001) adjusted the learning stages analyse, synthesize and evaluate into analyse, evaluate and create (Stanford Uni). When operationalising the demonstrated behaviour this study focuses on these higher-order thinking skills of Anderson et al (2001).
This study is about in what way can the critical thinking skills, operationalised with the learning taxonomy of Bloom, being amplified using PBL as strategy and simulation as facilitator.

Method

Participants in this qualitative study were eleven students in 7th grade, aged 11-13 years. Five of these students worked on the assignments alone, and six worked in pairs, resulting in eight times that the intervention was executed.

Procedure followed

The students were first given a short introduction about what the assignments are about. They were told that the simulations are about crowds in various situations. Their role was explained as coming to help to prevent that it is getting too crowdy and avoid congestion. The students were given a paper version of the questions and instructions (see appendix) and an A4 sheet with the symbols used for reference. After that, the target group was shown four videos in which the simulated situation was explained and finally asked for a solution of the given situation. In between, questions were asked via the video about what the target group saw happening, to keep the target group alert and to make them think about what is happening in the simulation and also prepare for a possible solution. The execution of the

assignments was recorded both by the observer in writing and by video for subsequent analysis.
Every session ended with an interview held by the observer in which the students were asked questions about how they liked the session, why they had given certain answers, what they had learned and whether they would like to see this way of 'teaching' more applied.

Intervention

Participants (alone or in pairs) received four assignments. Each assignment started with a video outlining a problem that could be addressed using SimCrowds. Students were asked to think aloud, while analysing the situation, answering questions and choosing a solution. They were asked to provide an explanation: Why they expected this solution to be the best. This solution was also written down on a worksheet by the student.
The assignments in short:

1. Students on their way to school, go to the supermarket for a long time. How do you prevent it from getting too crowded in the supermarket?
2. Pupils from various villages go to school via the station. Covid reigns. How do you prevent students from getting too close to each other?
3. A hallway in a school, the bell rings and classes are on the move. How do you prevent students from getting too close to each other in Covid time?
4. A shopping street where shoppers have to walk a fixed path. What is going wrong and how can you fix it?

Each assignment consisted of the following five steps:

Step 1: Watching the video

First, the student received a video in which a problem was outlined through simulation.

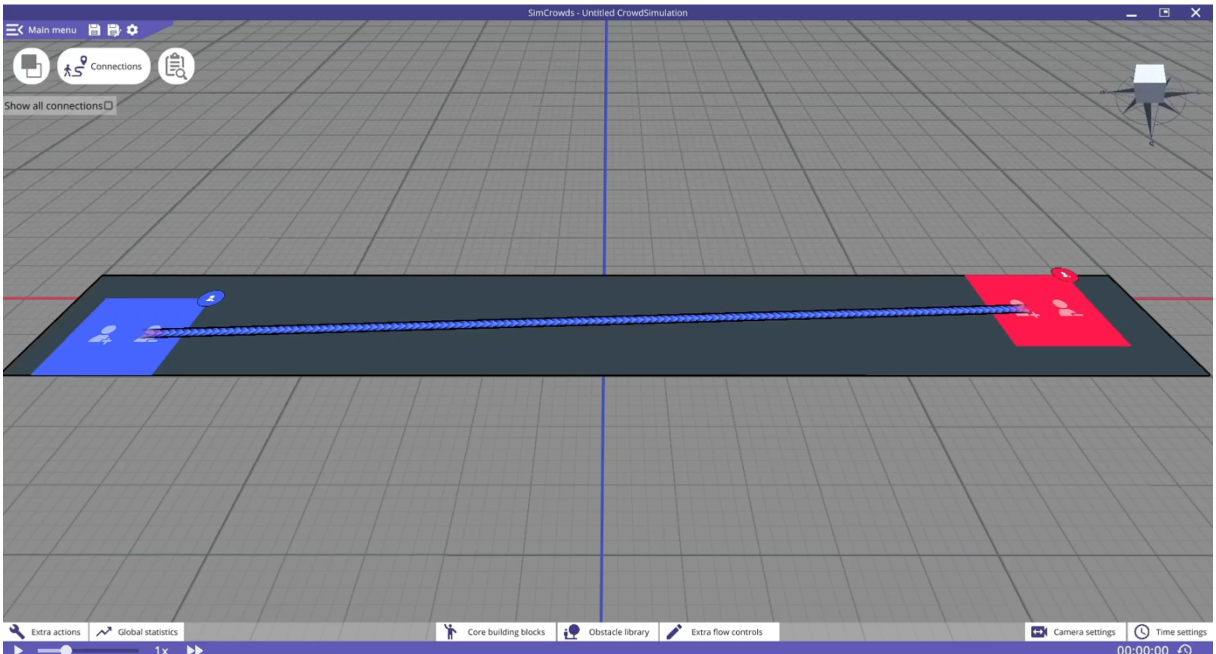

Figure 5: Video example assignment 3

Step 2: Answer preliminary questions and make a hypothesis

During the video, questions were asked to let the student devise a solution. These questions were, e.g.:

- Whether they saw something happen.
- If they could explain what was happening.
- How they thought they could fix this.
- Why they thought that was the best solution.

The given solution was recorded on the worksheet provided in advance.

Step 3: Adjusting simulation

The student then started the corresponding simulation in which the given situation was acted out. The student could apply the chosen solution and see what the result of this action was.

Step 4: Answering questions

After that there were some questions about:

- Whether the chosen solution worked.
- Whether the chosen solution had the effect that corresponded to what the student had thought up beforehand.
- Whether they would not have wanted to choose a different solution afterwards, including explanation.

The answers and explanation were also recorded on the worksheet provided in advance. As a result, during the concluding interview, they could specifically be cited with the question why they had come up with that solution.

Step 5: Possibility to give 2nd solution including answering questions – repeat steps 3 and 4

There was the possibility that after seeing the effect of the 1st solution, to apply a 2nd solution. And then answer and record the corresponding questions again.

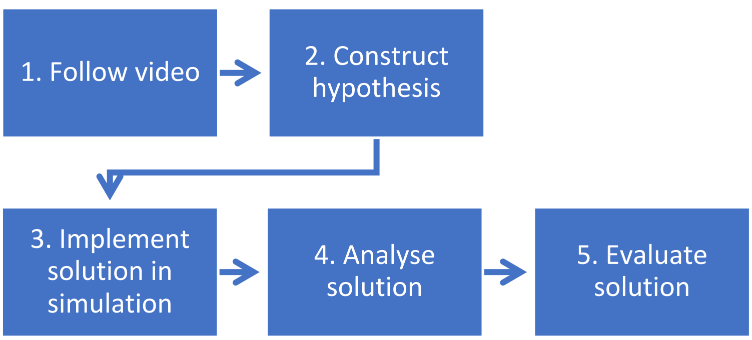

Figure 6: 5 steps of an assignment

Questions	Level
Can you explain what is happening?	Analyse
Can you see a solution to solve the problem?	Evaluate/Create
Can you explain what is happening now?	Analyse
Did you expect this outcome of your solution? Why?	Analyse/Evaluate
On hindsight can you think of a better solution?	Evaluate

Figure 7: Examples of questions stated and their level(s)

Data collection and analysis

A camera was used to register children progress in playing the simulation. An observer recorded the behaviour in writing. Also, in a worksheet given in advance, the solutions, given answers and explanations were recorded. Also, a concluding interview was held to record the experiences of the students. These interviews were noted on paper.

Data analysis

The footage of the children playing the simulation, the worksheet and closing interviews were studied in order to check whether a simulation in combination with appropriate instructions help in enhancing critical thinking. As mentioned, Blooms learning taxonomy was used for analysis. It offers a wide spread variety of verbs that is very useful to classify the actions of students to the expected levels of thinking. All the students' actions were converted into verbs based on this learning taxonomy. This process was repeated several times during the analysis.
After consecutive rounds it became clear that the analysis would not lead to an unambiguous result, for the following reasons:

- Sometimes actions belong to multiple verb groups.
- Some actions are inherent or successive to each other.
- Thinking process not always visible.
- Multiple versions of translation of revised Blooms taxonomy into verbs were available.

The first decision made was to use the revised version of Bloom's learning taxonomy of Anderson & Krathwohl (Anderson & Krathwohl, 2001).

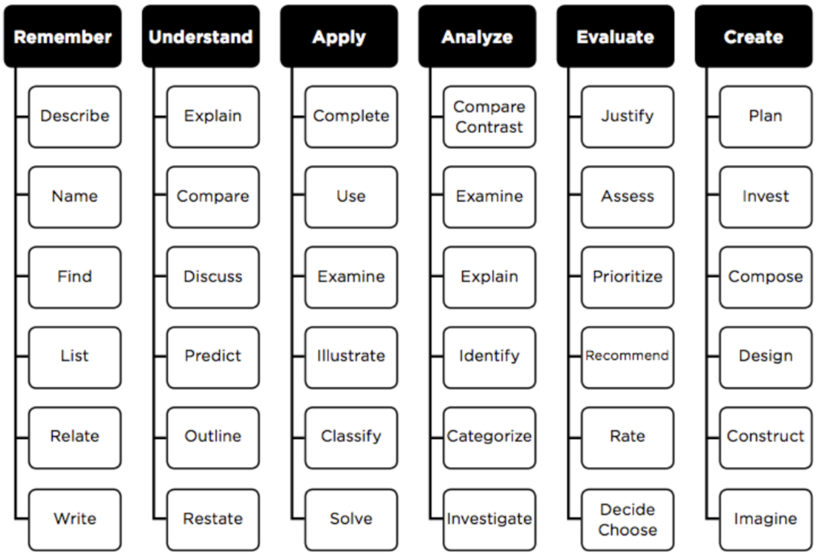

Figure 8: Subset of revised version of Bloom's learning taxonomy (Anderson & Krathwohl, 2001)

Also, in the chosen Bloom's version, the same verbs were seen in various places. In the example given above, see 'explain' in both the understand phase and the analysis phase.

Above all, this study focused on the higher-order processes as representing critical thinking in the context of simulation-based learning. Eventually the following subset of verbs that were included in the analysis was chosen, with verbs most frequently referred to in red.

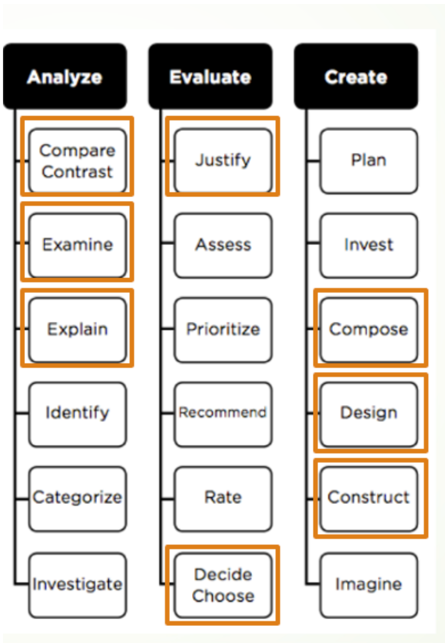

Figure 9: Used taxonomy subset

Below an example of a final transcript of the students' actions (left) and its analysis (right).

> Student: "Oh, oh, okay, so this doesn't work."	> Concludes: 'Oh, oh, okay, so this doesn't work.' (Analyse)
> Student: "I can see that the lines are starting to intersect and they are starting to get too close."	> Compare: "I can see that the lines are starting to intersect and they are starting to get too close." (Analyse)
> Student makes hand gestures to clarify the situation for himself and why it is not working as expected.	> (Explain/Justify) Makes hand gestures to clarify the situation for himself and why it is not working as expected. (Analyse/evaluate)
> Student: "I could set distance, then they will have the keep their distance."	> (Examine/decide) Thinks up/chooses new solution: "I could set distance, then they will have the keep their distance." (Analyse/evaluate)
> Student applies new solution.	> Applies new solution. (Analyse/evaluate/create)

Figure 10: Example analysed behaviour student

Results

As can be seen in the charts below, students are using the higher-order thinking capabilities when triggered. The behaviour shown clearly demonstrates that higher-order thinking can be stimulated by simulation in combination with appropriate instructions and questions.

Result of study

The following graphics show a considerable use of higher-order skills during the sessions.

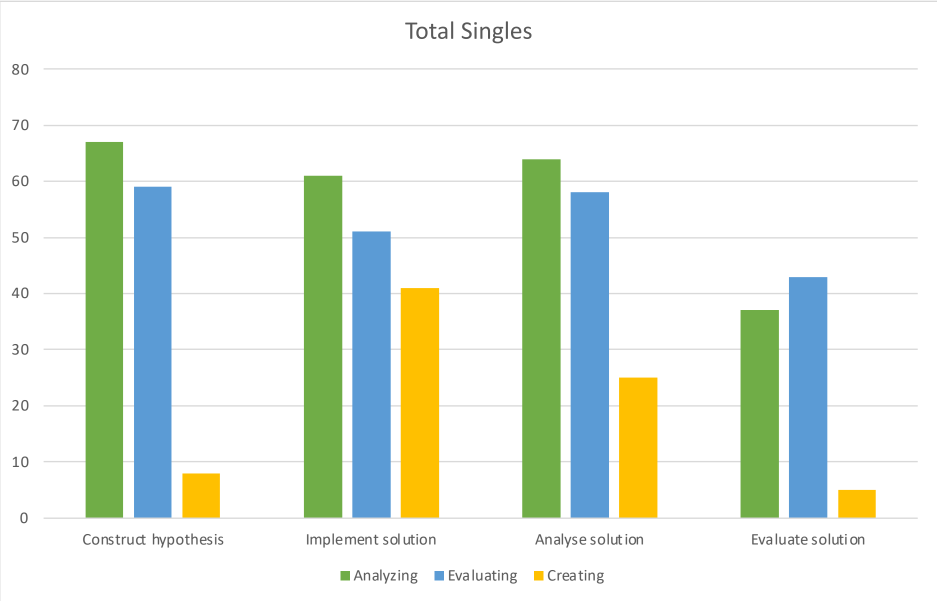

Figure 11: Counted use of higher-order skills as demonstrated by singles (5)

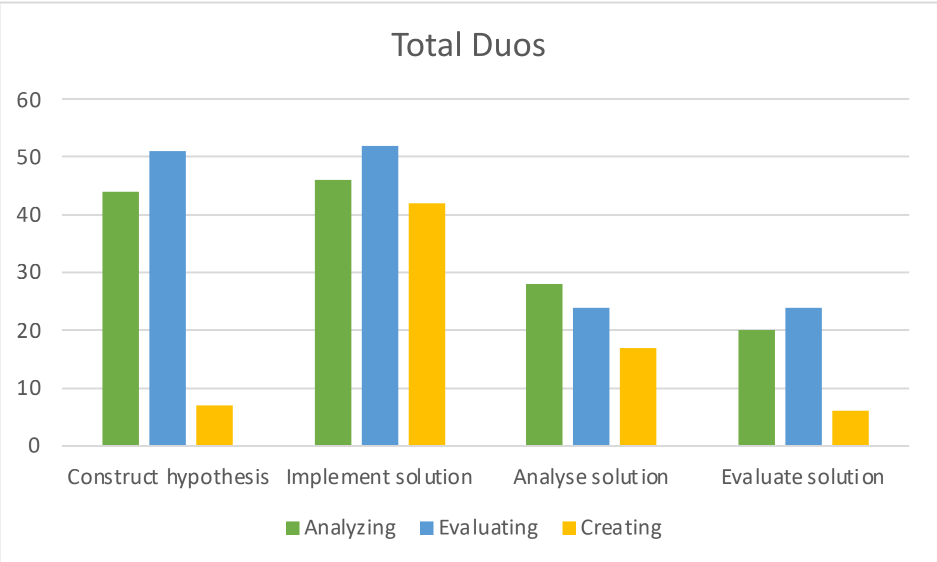

Figure 12: Counted use of higher-order skills as demonstrated by duos (3)

Regarding singles or duos

Because the study had a classification of singles and duos, the difference in applying higher-order thinking could also be represented. There were three duos and five singles. The total result can be seen in Figures 11 and 12. Figure 13 below gives an overview for which the results of the duos have been adjusted, so that the total results could be compared.

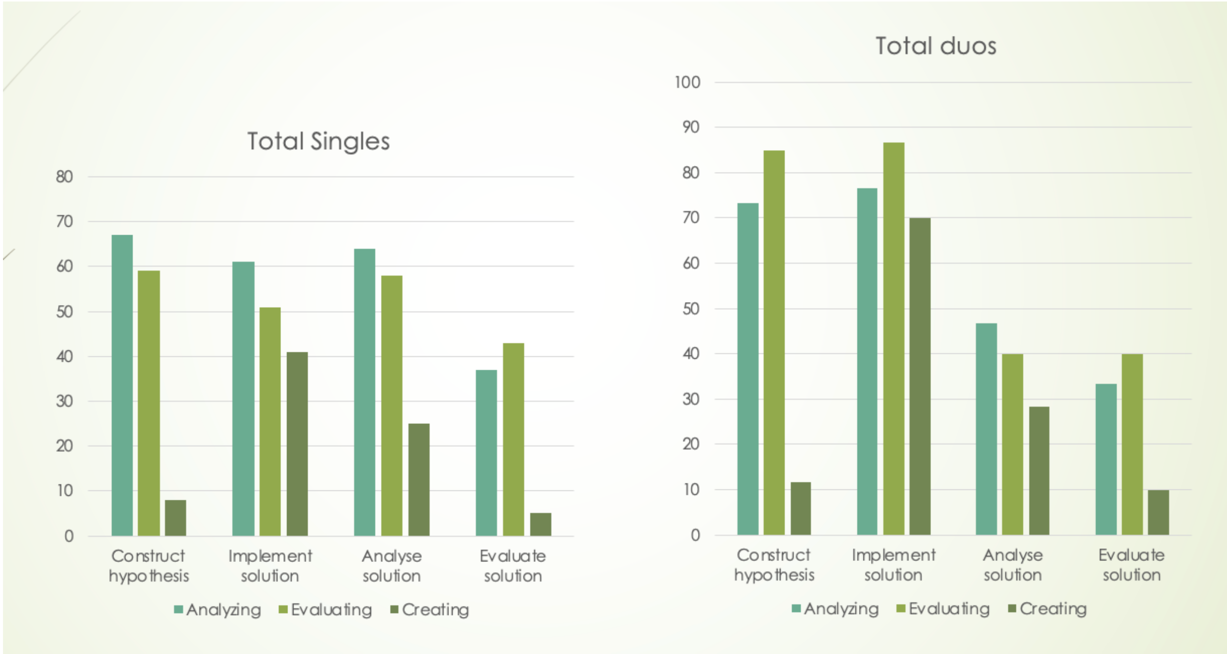

Figure 13: Comparison counted use of higher-order thinking between Singles and Duos. As can be seen, the graphics of duos demonstrates more use of higher-order thinking, especially in Evaluating and Creating.

Use of closing interview

In the closing interviews, the students were asked about their experiences, why they had given certain answers, whether they would like to give different answers afterwards and whether they would like to be taught accordingly if possible.
Without exception all contenders were very enthusiastic. They were really thinking about their own thinking and learning. Below some of the experiences of the students:

- "That you could decide for yourself, what you could do. That you can think along how it can be and which solution works. It was interesting whether your own ideas worked."
- "I think you will learn better because of this. You find easier, faster solutions to problems. You can then remember better."
- "We quickly had a solution, but if we had thought more about it beforehand, we would have come up with another solution."
- "I can follow instructions at my own pace and It helps me that if I do it myself, that the problem becomes clearer and I can learn from my mistakes."

Appearance of trial and error

During these sessions, a lot of trial-and-error behaviour was seen. The students encountered new situations and tried different possibilities. What worked, was remembered and carried out permanently, but if it didn't work, the students looked for other ways, until the desired result was achieved.

Apply solution before starting the game. Discuss how to do it. "I wouldn't do that, because then people would get too close to each other."

Ask: "How can you make such a line again? Oh, wait I already know."

They consult and complement each other well. (4/5/6)

"Okay, let's take a look."

Analysing: "Oh, wait a minute, it's getting too busy. We have to remove this (point to screen)." (4/5)

Come up with a new solution: 'Maybe we can do this too, ... one more, and then we'll stop it.'

Ask: "Can we create a new solution?" Create a new (2nd) solution.

Figure 14: Example of trial-and-error behaviour. Figures refer to the used higher order thinking.

Conclusions

This study provides insight into the use of critical thinking skills using simulation and including instructions and guidelines as facilitator. The expectations that existed beforehand on how the students experienced solving recognizable problems in a simulation context and how their critical thinking skills benefit from this, are matched. This finding is backed up by literature. According to Veenman et al (1994), problem-oriented simulations help develop higher-order thinking strategies and improve student cognitive abilities employed in the service of recall, problem-solving, and creativity. Present study adds a facilitator to the simulation to guide the students actively into critical thinking. It illustrates that simulation supports higher-order thinking skills when used with appropriate facilitation.

Additionally, forcing the students to construct their own hypothesis, according to Quinn and Alessi (1994), and having them to analyse and evaluate their own hypothesis stimulates their thinking about how they think and learn. Having to think up a solution activates the brain more than being presented with possible solutions to choose from.

Thirdly, this study proves that students want to work with real-life problems. Simulation provides a challenging environment in which real-live problems can be studied and solutions to these problems can be tested, analysed and evaluated. Students found this way of working very stimulating. The most given reaction during the closing interviews was: ‘I can give a solution to an existing problem and can actually see whether it works in reality.’.

Discussion

Regarding simulation as facilitator

Initially, the intention was that simulation was the sole facilitator and that the necessary instructions, questions and symbol map also would be given and explained by the simulation. This meant that SimCrowds would have to be adapted accordingly. Due to a lack of time and manpower to adapt the underlying software, it was decided to include the instructions and questions in an accompanying instruction video and worksheet. A separate chart with symbols where the student could look back for explanation of the used symbols in SimCrowds, was also made. In itself, this choice did not detract from the study result, because it allowed the students to examine things and answer questions at their own pace.

Regarding singles or duos

The differences seen in outcome (as seen in figure 13) from this comparison are:

1. Duos discuss more with each other, so their thinking process can be more followed. There was more data to analyse.
   E.g. during the video with instructions, duos already discussed what would happen and what a possible solution would be.
2. Also, the duos inspired and challenged each other more into trial-and-error behaviour. They dared more.

However, there is no unambiguously conclusion to be drawn whether the singles or duos are faster or better in applying higher-order thinking. When asked, the singles indicated that they prefer to work alone because they are (usually) limited or hindered by collaboration:

- ‘I think much faster than others.’
- ‘I can't think when someone next to me thinks out loud.’

Regarding instructions

Because time is limited and children cannot continue to play indefinitely, it is good to give guidance so that they remain on the right track. The given instructions should be such that children start thinking about their own steps. You have to ‘force’ them by appropriate questions to reflect on their own behaviour and on what they have done so, if it is not the desired result, that they can retrace their steps. This step-by-step structure, in conjunction with self-discovery, ensures that students develop more problem-solving skills.

Limitations

The translation of the observed behaviour of students into Bloom's higher-order thinking is not unambiguous. Undoubtedly, different translations are possible. There will be discrepancies if various people make the same effort for this translation. The translation has been done to the best of our knowledge and as objectively as possible.

The participants in this qualitative study were eleven 7th graders. Therefore, the results are limited and not representative of all 7th graders.

This study only concerned pre-university education students. It is therefore not representative of all students.

Recommendations

Given the results of this study, it is recommended that the student describes the problem and a solution in his/her own words and then solves the problem using the simulation. By using problem-posing the student develops insight and already gets a better sense of what a possible solution can be.

This study also illustrates that is it recommended that the given situations should start small. Scaffolding in difficulty gradually gives the student the opportunity to acquire and apply knowledge. Start small and increase in difficulty step-by-step. As a result, students gradually learn the possibilities of the simulation and develop their self-confidence, and are challenged to explore more possibilities.

The last recommendation concerns the facilitator. In this study, as mentioned before, it was not possible to build all instructions and guidelines in the simulation and was decided to include the instructions and questions in an accompanying instruction video and worksheet. That was not a problem in hindsight. By offering variation in the instructions and guidelines, students are triggered in different ways to acquire and use knowledge. In this way, the material presented can be taken up in different ways by various students.

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