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Does drawing help or hinder creativity when solving a modelling problem? Findings from an eye-tracking study

Abstract. Solving a mathematical modelling problem is an activity that allows students to be creative. In the current study, we recorded the eye movements of two students while they solved a geometry modelling problem with instructions to make a drawing, and we conducted a stimulated recall interview (SRI). Using qualitative content analysis, we coded the gaze-overlaid videos and SRI with respect to students' modelling processes and their levels of usefulness, fluency, and originality. We found that the levels of originality and fluency varied during the modelling process, indicating that modelling processes involve creativity and that the final solution might not fully reflect students' creative processes as they work through a problem. In addition, we describe how constructing and using a drawing helped or hindered students being creative. Findings are discussed regarding future studies on creativity in mathematical modelling and implications for classroom practice.

Keywords. Creativity, mathematical modelling, drawing, eye tracking.

Mathematics Subject Classification: 97C30, 97M99.

1 - Introduction

Creativity is considered a key 21st-century skill in a rapidly changing and interconnected world. Thus, it is an aim of mathematics education to equip students with the abilities to use their mathematical knowledge and abilities in a flexible manner so that they can develop solutions to unsolved problems and create new ideas and innovations. Previous research indicates that mathematical modelling is an activity that demands creativity [**7**]. However, students'

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written solutions indicate low levels of creativity [**7**]. Thus, research is needed on how to promote students' mathematical creativity in modelling. In the current study, we explored the creative processes of two secondary school students while they solved a geometry modelling problem, and we explored drawing instructions as a tool for promoting creativity.

2 - Mathematical creativity

Mathematical creativity is creativity that is specific to the field of mathematics, including a student's abilities to generate novel, unusual, and appropriate ideas and outcomes during problem solving [**5**]. According to a common notion of creativity [**4**], creativity includes different aspects that can be used to identify creative thinking in problem solving [**9**]: Originality includes original and rare ideas or solutions and is considered the predominant characteristic of creativity. Fluency describes the identification of multiple solutions, and usefulness refers to the appropriateness of the approach taken to solve the problem and its transferability to similar problems. A student's level of mathematical creativity can be evaluated in relation to their previous experiences and to the performances of peers with similar educational backgrounds (i.e., relative creativity [**6**]). Previous research has shown that students' levels of mathematical creativity are positively related to their mathematical abilities, indicating that mathematical creativity is a subcomponent of mathematical abilities [**5**]. Considering the importance of developing students' creative abilities in mathematics, research has looked for ways to promote students' creative thinking through activities and tasks that trigger mathematical creativity [**9**].

2.1 - *Creativity in mathematical modelling*

Mathematical modelling is considered a creativity-demanding activity [**7**, **16**]. Modelling includes the application of mathematics to solve real-world problems and is a core mathematical competency in many curricula all over the world [**1**]. Modelling activities are usually initiated by so-called modelling problems (Figure 1). A modelling problem is a nonroutine real-world problem that provides students with opportunities to consider a variety of standard and original realistic details, choose between useful real-world and mathematical models, apply different solution methods, and arrive at multiple solutions [**1**].

Until now, there has been little research on creativity in mathematical modelling. Lu and Kaiser identified originality, fluency, and usefulness as aspects of creativity in secondary school students' written solutions to modelling prob-

Cable car

Since December 21, 2017, a state-of-the-art cable car has been allowing people to access Germany's highest mountain, the Zugspitze. The construction of the cable car, with which the summit of the 2,962-meter-high mountain can be reached from the valley in under 10 minutes, cost around 50 million euros. The cable car overcomes a horizontal difference of 4,021 meters and a height difference of 1,945 meters. The two glass-enclosed cabins are moved by a traction cable, and each cabin is carried by two ropes that are looped around massive spools several meters in diameter in the stations. After about a quarter of the way to the summit, the cabins pass the only 127-meter-high steel support. How many meters of rope were needed for the ropes that carry the cable car?

Fig. 1. Exemplary modeling problem: *Cable car*.

lems [**7**]. However, the students in their study tended to show only low and medium levels of creativity. For example, most students generated one solution to a modelling problem. Only a few students used ambitious mathematical approaches or considered original parameters, and a large proportion of students generated approaches that were useful only for specific problems and lacked transferability to other similar problems. However, research on creative end-products does not provide full insight into the creative processes that result in the creative end-products. Thus, the current study was aimed at tracing the creative process while students solved a modelling problem to further explore the potential of modelling to trigger creative thinking. Students' low levels of creativity further inspire the question of how creativity in modelling processes can be promoted. In the current study, we explore how making a drawing can help or hinder creativity in modelling.

2.2 - *Creativity and drawings in mathematical modelling*

The strategy of self-generated drawing in the context of mathematical modelling describes the construction and use of a drawing to find a solution to a modelling problem. A drawing is defined as a structurally analogous representation of the mathematical problem structure, arranging objects on the paper according to their relationships. In a drawing for a modelling problem, objects can be drawn pictorially or reduced to their mathematical characteristics (situational and mathematical drawing, respectively; Figure 2). Previous research indicates that drawing use and drawing accuracy are positively related to students' modelling performance [**10**]. Asking students to make a mathematical drawing seems to be particularly effective for students' performance [**11**]. Theories of problem solving have stated that drawing can support problem solving by organizing the information in ways that are useful for solutions and by laying out the range of possible models. These steps can be accomplished by making important information explicit and representing implicit information explicitly to facilitate perception and retrieval [**2**]. Analogously, drawing has the potential to facilitate usefulness, fluency, and originality as aspects of creativity. However, to the best of our knowledge, the relationships between drawing and creativity have not yet been investigated. It is an aim of the current study to explore how making a drawing for a modelling problem helps or hinders creativity in the modelling process. Eyetracking methodology might provide insight into creativity and drawing-related processes of perception and retrieval, which are otherwise difficult to observe.

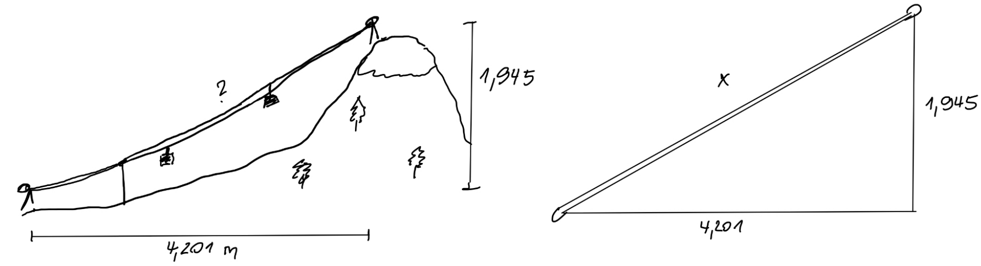

Fig. 2. Exemplary drawings for the *Cable car* modelling problem.

3 - Research questions

In the current study, we explored students' creative processes while they solved a geometry modelling problem with instructions to make a mathematical drawing. The research questions were as follows: (1) How do levels of originality, fluency, and usefulness develop during the modelling process? (2) How can drawing help or hinder originality, fluency, and usefulness when solving a modelling problem?

4 - Method

4.1 - *Participants and procedure*

Four high-achieving students in Grade 10 at a German comprehensive school (Gesamtschule) participated voluntarily and anonymously in this study. For the in-depth analysis, two participants (15 and 16 years old) were selected because their written solutions indicated maximum variation in their creativity levels [**8**]. The study was conducted in individual sessions in an unoccupied classroom during students regular mathematics classes. First, students read a written explanation of the situational and mathematical types of drawings for an exemplary modelling problem. Then, students worked on three modelling problems with mathematical drawing instructions, recording their eye movements. The cable car problem was the second problem they worked on. After students had finished, a stimulated recall interview (SRI) based on the gaze-overlaid video was conducted to gain deeper insights into students' modelling processes [**14**]. For example, students were asked for additional explanations if statements remained unclear or ambiguous during modelling.

4.2 - *Apparatus*

We used a mobile eye-tracking glasses system (Tobii Pro Glasses 3, 50 Hz sampling, 0.6° gaze estimation accuracy) to record students' eye movements. The mobile eye-tracking glasses allowed students to use paper and a pencil and to move their heads around freely. The materials were printed on a horizontal piece of paper of size A4 (Figure 3) to match the glasses' field of view of 95° x 63°. We used a tiltable table to optimize the angle between the material and the student's eyes in order to reduce measurement errors. Before each modelling problem, the eye-tracking glasses were calibrated through a one-point-calibration procedure. Two master's students were seated behind the participating student's back and monitored the collection of the eye-tracking data on the computer.

4.3 - *Data and data analysis*

4.3.1 - Coding of creativity levels

To systematically identify aspects of students' creativity in students' modelling processes, we applied a qualitative content analysis [**8**]. We followed a detailed coding manual that accompanied the MAXQDA 2022 software to code the video of students' modelling processes, complemented by students' SRI statements. Lu and Kaiser's category scheme [**7**] was used and adapted to the cable car problem (e.g., orginal parameters were specified; Table 1), as it allows to rate components of creativity in modelling activities. The reference values required to assess a student's relative level of originality compared to a peer group of similar educational experiences stem from an analysis of 57 tenth grade students' solutions of the cable car problem. In the first step, video sequences were assigned to the three aspects of creativity (i.e., originality, fluency, and usefulness). In the second step, the level of creativity was rated as low, medium, or high. The first author and an external coder independently applied the category scheme to the videos with acceptable intercoder agreement (Cohen's $\kappa > .71$).

Table 1. Subcategories for the levels in the aspects of creativity in students' solution process/solution

Creativity component	Level	Description for the *cable car* problem
Originality	High	The student considered parameters (e.g., the curvature of the rope, the rope rolled around the spools, the steel support, or the cable car's starting height) and mathematical concepts (e.g., two right-angled triangles or a parabola) used by less than 10% of students.
	Medium	The student considered parameters and mathematical concepts (e.g., two ropes) used by 10% to 30% of students.
	Low	The student considered parameters (e.g., horizontal and vertical distance) and mathematical concepts (e.g., one right-angled triangle) used by more than 30% of students..
Fluency	High	The student considered more than one model (e.g., different parameters, different mathematical models) in their solution process/solution.
	Medium	The student considered one (mathematical) model (in most cases one right-angled triangle without additional parameters) in their solution process/solution.
	Low	The student did not develop a model/solution (e.g., blank or restatement of the problem).
Usefulness	High	The student considered algebraic expressions, inequalities, or functions to describe the situation in their solution process/solution.
	Medium	The student considered only specific values to describe the situation in their solution process/solution.
	Low	The student did not develop an adequate mathematical model in their solution process/solution.

4.3.2 - Analysis of eye movements

To trace students' eye movements, we defined four areas of interest (AOIs) on the worksheet (Figure 3). We used the Tobii Pro Lab (Version 1.181.37603) software and the default setting of the Tobii I-VT Fixation Filter to detect fixations inside our AOIs. AOI sequence charts (Figure 5) generated with the R package AOIanalyseR [**13**] illustrate sequence and duration of student's fixations. We used drawing-AOI hits to identify phases of drawing construction and use, that were then analyzed in depth regarding creativity.

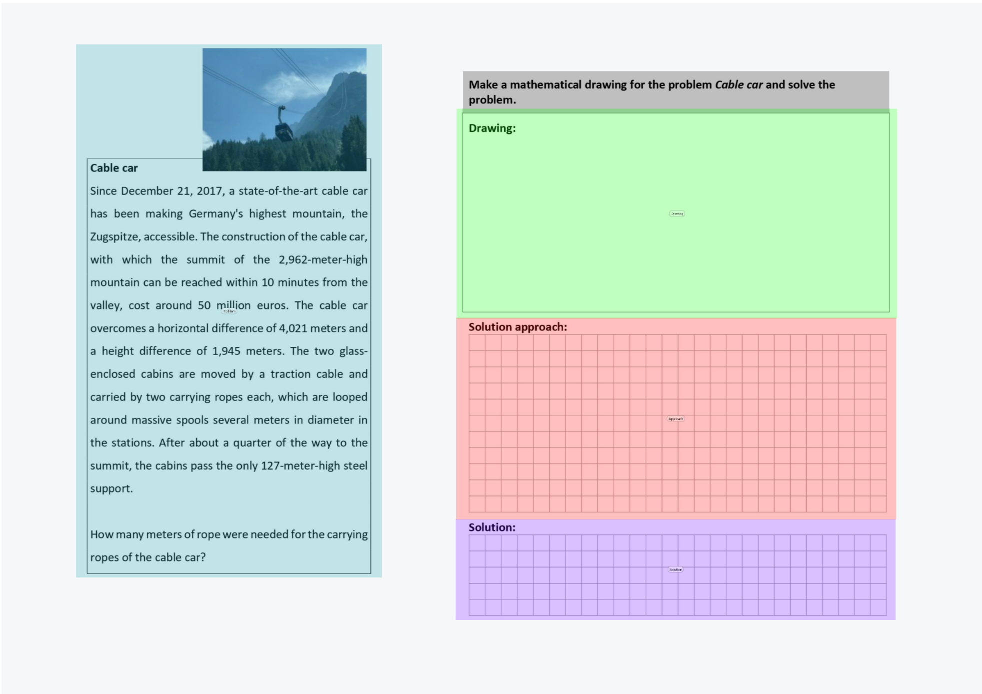

Fig. 3. Working sheet with overlaid areas of interest (AOIs).

5 - Results

Students' written products and AOI sequence charts are shown in Figures 4 and 5.

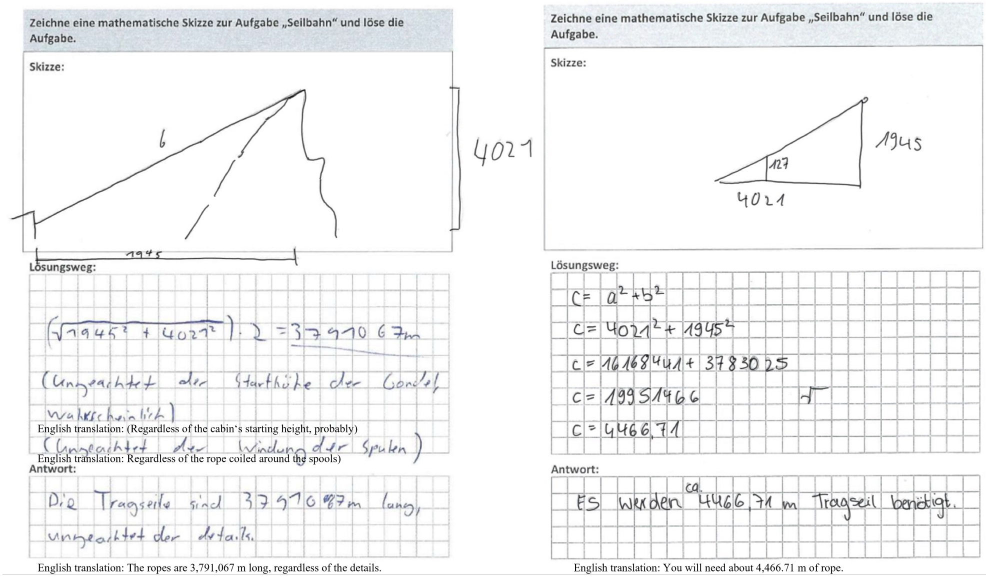

Fig. 4. Lukas' (left) and Tamara's (right) written records.

5.1 - *How does creativity develop during the modelling process?*

Regarding the manner in which creativity develops during the modelling process, we found that the levels of originality and fluency varied during the modelling process from low to high levels and differed from the final solution's creativity level (Figure 5). We found little to no variation in usefulness within the modelling process itself or between the modelling process and the final solution. Lukas demonstrated low, medium, and high levels of originality in the phase that involved understanding and developing a real-world model as he underlined the information about two ropes in the text (0:00:52), drew the mountain (0:01:50), drew a straight line to represent the rope (0:01:57), and sketched the valley station (0:02:00). In the SRI, with respect to the process of drawing the rope, he added, "And what I also noticed there, but what I simply didn't write down because I knew that it would be far too much text, is that the ropes can never run 100% straight" (SRI 0:15:59). In developing a mathematical model (i.e., setting up an algebraic term) (0:02:42-0:03:18), Lukas demonstrated high levels of originality again because he additionally considered the 127 m-high steel support, the exact location of the mountain station relative to the top of the mountain, and the rope that was rolled around the spools: "And I think that's when I thought about the spools again. [...] And that I don't ride it directly to the top of the mountain, of course, and that it's not [...]

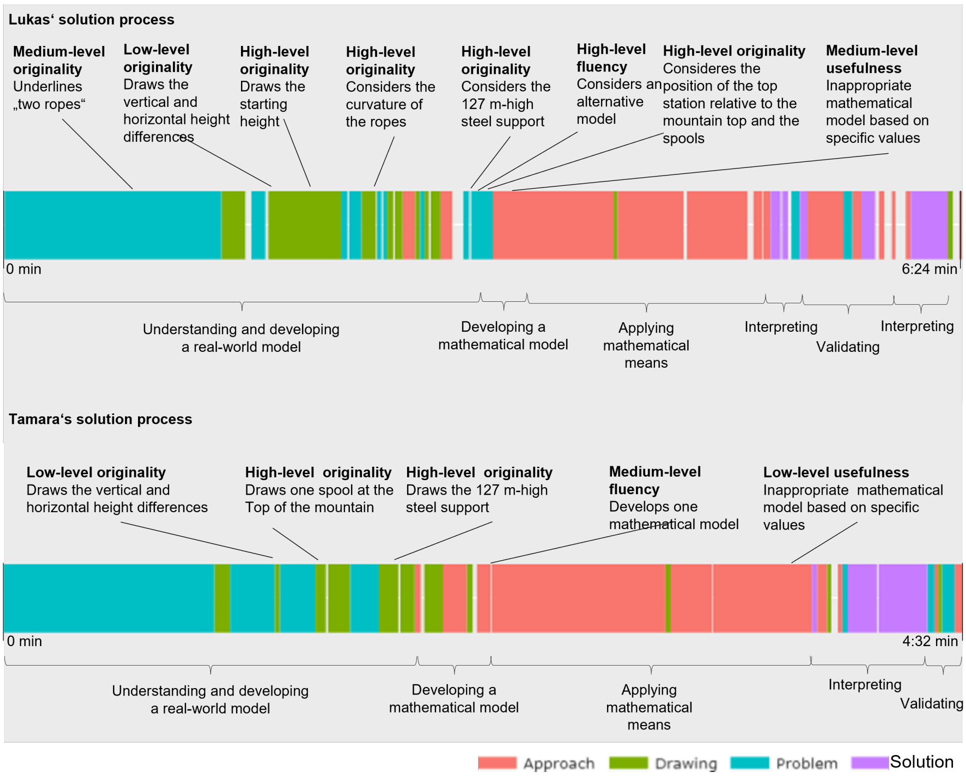

Fig. 5. AOI sequence charts.

attached to the top of the top, but probably a bit below. I simply calculated using the values that I knew. And basically, making assumptions in math is always such a difficult thing, so if I would have said that the cable car station on the Zugspitze was 200 meters below the absolute top of the mountain, I think it would all have been a bit vague" (0:18:34) and "I thought about including this [the steel support], but I think that would mean I'd still be working on the task" (SRI 0:17:50). Working with his mathematical model (0:03:27-0:04:10), Lukas showed medium originality because he considered the horizontal and vertical height and the presence of two ropes. After interpreting his mathematical result, Lukas validated his solution, which resulted in a final high level originality because he acknowledged that his omissions of the starting height and spools were limitations of his solution (0:04:36 and 0:05:25). Tamara showed low to high levels of originality in the phase involving understanding and developing a real-world model because she drew the horizontal and vertical distances (0:01:18-0:01:34), a spool at the mountain station (0:01:35), and the steel support (0:01:36). After developing a mathematical model (0:02:07), her modelling process and final solution were considered to have a low level of originality because she only considered parameters (horizontal and vertical difference) that were used by a large number of peer students. Lukas demonstrated a high level of fluency in the phase involving developing a mathematical model (0:03:18) because he considered an alternative mathematical model: "And at that moment, I think I thought about whether it would not have been more effective to use a parabola in the end. Because you can really see [in the picture] that it's bent" (SRI 0:17:15). Lukas decided to use the simpler model, thus demonstrating a medium level of fluency in his final solution: "I thought about including this [the curved rope], but I think that would mean I'd still be working on the task. [...] Two parabolas would have formed that rope, [...] so I thought, come on, the Pythagorean theorem is faster" (SRI 0:17:15). Tamara demonstrated a medium level of fluency in her modelling process and in her final solution: She developed one mathematical model (0:02:07) and did not mention alternative models in the SRI. Lukas demonstrated a medium level of usefulness during the phase involving understanding and developing a real-world model reflected in the process of drawing construction (0:02:00). Because he labeled the drawing incorrectly (0:02:05), he then showed a low level of usefulness until he provided his final solution. Tamara did not consider important information (two ropes) up to the phase involving understanding and developing a real-world model. Thus, her modelling process and final solution were characterized by a low level of usefulness.

5.2 - *How can drawing help or hinder creativity?*

To explore the relationships between drawing activities and aspects of creativity, we conducted an in-depth analysis of sequences with fixations in the drawing-AOI and observations of the aspects of creativity. Overall, we observed sequences in which drawing construction or exploration seemed to promote creativity in students' solution processes, but we also observed some in which creativity seemed to be impeded by drawing. Constructing a drawing promoted originality in Lukas' modelling process because drawing the valley station made him think about the cabin's starting height (0:02:00) and drawing the rope made him reflect on the rope's curvature (0:01:57). In addition, his exploration of the drawing while mathematizing the problem triggered original ideas again because Lukas reflected on the exact location of the mountain station (SRI 0:18:34). Therefore, we conclude that constructing a drawing forces students to make certain information explicit in the drawing (e.g., how the rope runs and how it is attached to the stations) and thus directs their attention toward the original parameters. Drawing exploration triggered students to reconsider these and additional parameters. In Tamara's modelling process, drawing promoted originality as she drew the steel support and one spool at the mountain station. Thus, her attempt to construct an adequate representation of the problem situation in the drawing made her consider the original parameters. However, Lukas and Tamara did not include all the relevant parameters (e.g., two ropes) in their drawings. Lukas underlined the information in the text (0:00:52) and integrated the information into his mathematical model by referring to the text (0:03:18). Tamara did not consider the second rope in her modelling process. Thus, omitting relevant parameters from the drawing impeded the originality of Tamara's modelling process and her final solution, whereas Lukas was able to still incorporate the important information. Constructing and exploring the drawing promoted fluency for Lukas but not for Tamara. When Lukas attempted to specify the course of the rope in his drawing (0:00:57), he considered drawing a curved rope (SRI 0:15:59). He reconsidered this idea by considering modelling the rope with two parabolas when he looked at the drawing to set up an algebraic term (0:03:18). We did not observe that Tamara considered another model when she constructed or explored the drawing, and this failure to consider another model might have prevented her from thinking about alternatives in later phases of the modelling process. Thus, we conclude that constructing and exploring a drawing promoted fluency in Lukas' modelling process but not in Tamara's. Constructing the drawing and using the drawing to set up an algebraic term hindered usefulness in Lukas' and Tamara's solution processes. Lukas labeled the drawing incorrectly (0:02:05) and translated the incorrect information into his inadequate mathematical model (0:03:18), as his eye movements indicated that he got the numbers from his drawing (0:02:57). Tamara did not include important information about the number of ropes in the drawing and translated the incomplete drawing into an inappropriate mathematical model by using the numbers from her drawing (0:02:07). Thus, using an incorrectly labeled or incomplete drawing for mathematization hindered usefulness for both Lukas and Tamara.

5.3 - *Discussion*

Helping students develop mathematical creativity is an important goal in equipping students for the challenges of the world when they finish school [**16**]. Modelling problems have the potential to elicit creativity in students. However, the levels of creativity in solutions for modelling problems generated by students was previously found to be low [**7**]. In the current study, we explored students' levels of creativity during the modelling process and how making and using a drawing could help or hinder creativity. On the basis of our qualitative analysis, we generated hypotheses that need to be tested in future studies with quantitative study designs.

5.3.1 - How does creativity develop during the modelling process?

We used Lu and Kaiser's coding system to rate students' levels of originality, fluency, and usefulness during their modelling process and in their final solutions [**7**]. Consistent with previous research, we found low levels of creativity in the students' solutions. For example, like most participants in the study by Lu and Kaiser [**7**], Lukas and Tamara generated one mathematical model and predominantly considered commonly used parameters in their solutions. In addition, usefulness was low in the current study, which reflects students' difficulties in carrying out the modelling process [**3**]. However, the analysis of students' solution processes adds to previous research as it revealed that the levels of the three aspects of creativity that students demonstrated as they moved through the modelling process were higher than was reflected by their final solution. For example, Lukas and Tamara considered original parameters (e.g., the location of the mountain station or the spools) but decided not to incorporate these parameters into their final solutions. Lukas evaluated alternative mathematical models (i.e., modelling the rope by using the hypothenuse of a right-angled triangle or a parabola) but finalized one solution that was based on one mathematical model. One explanation that Lukas gave in the SRI for omitting some of the original parameters or an alternative model in the final solution was that he wanted to save time and effort by focusing on the simpler but less adequate mathematical model (SRI 0:17:50 and 0:18:34). Thus, a student's motivation might impact the creativity level that the student demonstrates in their modelling processes and solutions. Other explanations involve students' prior knowledge and experiences with modelling instruction, indicating that students need to be explicitly asked to make multiple solutions to increase their number of solutions [**12**]. Still, our findings underscore Lu and Kaiser's conclusion that working through the mathematical modelling process requires creative thinking [**7**]. Thus, modelling might be helpful not only for understanding mathematics, understanding reality, and applying mathematics but also for being creative.

5.3.2 - How can drawing help or hinder creativity?

The second aim of the current study was to explore how drawing can help or hinder creativity in mathematical modelling. For originality, we found that students came up with highly original ideas before, during, and after constructing a drawing. For example, Tamara drew one spool at the mountain station, and Lukas reflected on the curvature of the rope before representing it in his drawing. This phenomenon is supported by the Cognitive Theory of Drawing Construction [**15**], which states that the student needs to select, organize, and integrate the relevant information that can be externalized in the drawing into a coherent model. Externalization comes along with the need to make implicit information explicit (e.g., the location of the mountain station) [**2**]. Thus, drawing might trigger students to consider original parameters in the modelling process. The current case studies seem to indicate that drawing details might stimulate reflections on additional parameters, thereby contributing to originality. Future studies should investigate whether situational and mathematical drawings affect originality in the modelling process differently. For fluency, we found that constructing and exploring the drawing promoted Lukas' fluency, as it triggered him to consider an alternative model. Again, this observation can be explained by the Cognitive Theory of Drawing Construction [**15**] and theories of cognitive representations [**2**], as drawing requires the drawer to make information explicit (e.g., the form of the rope). At the same time, Tamara's case showed that specifying objects and relationships in a drawing can restrict the space in which students search for models and ways to approach their solutions. A restricted solution space might hinder creativity and result in low levels of fluency. For usefulness, we observed in Lukas' and Tamara's cases that making an inaccurate drawing led to an inadequate mathematical model and solution (i.e., a low level of usefulness), as Lukas' and Tamara's eye movements indicated that both of them used their inaccurate drawing to generate the mathematical model. This observation is in line with current research that has revealed a positive relationship between drawing accuracy and finding an appropriate mathematical model [**10**]. Correspondingly, making and using an accurate drawing might promote creativity in terms of usefulness. Overall, we conclude that making a drawing can help students be creative but can also hinder their creativity. It is up to future research to investigate the conditions under which drawing promotes the various aspects of creativity. Analysis of students' eye movements is a promising approach to identify drawing-related processes: In the current study, it helped identify phases in which students fixed the drawing for exploration or validation, which would be difficult to detect with video observation. Furthermore, gaze-overlaid videos helped students recall their considerations during modelling, giving insight into creative processes that were not reflected in written records. Still, eye movements need to be interpreted with caution, since they reflect, among other things, affective arousal in addition to cognitive processes [**14**].

5.4 - *Practical implications*

Our finding that students engaged in creative thinking while solving modelling problems supports the claim that modelling problems are activities that demand creativity and are thus suited for teaching mathematical creativity in school. To support creativity during the modelling process, teachers should value and give students the space to share successful and unsuccessful ideas, models, and procedures that go beyond standard solutions; they should expand the individual creative space by collaborative work; or they should ask students to generate multiple solutions [**12**]. As the current study showed that creativity levels during the modelling process might differ from the solution's level of creativity, it is particularly important to present and discuss not only students' final solutions but also their different approaches, strategies, and procedures in class. Generally, the independent use of self-chosen strategies is part of creative modelling [**16**]. As students struggle with modelling and creativity, one intervention that teachers can offer might be to instruct students to make use of the drawing strategy, as previous research has pointed to the potential of the use of drawings to support modelling [**11**], and the current study indicates that constructing and exploring a drawing can promote originality, fluency, and usefulness.

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