The influence of mechatronic learning systems on creative problem solving of pupils participating in technology class

A pilot study

Kai-Christian Tönnsen, Patric Schaubrenner

Without being creative and finding solutions for various problems of life mankind wouldn't be what it is today. Problem solving always has been a key ability for development, in the past, the present and it will also be a key for the future. Creative problem solving is one of the most important ways of technical thinking and acting. Therefore, the ability of finding solutions for problems and realizing them is a primary goal for technological education, especially if it is part of a comprehensive school education. It can be assumed that the available resources affect the possibilities and the result of problem solving processes. In terms of technology classes there are numerous resources that aim for the development of pupils' creative problem solving skills like for instance mechatronic educational environments (MEEs). Unfortunately there is currently no test instrument for rating the influence of these MEEs on the outcome in terms of creative technical problem solving processes. Therefore, we designed a trial for such purpose and tested it in a pilot study: 33 students (9th grade, average age of 15.24 years) of comprehensive schools were given a problem, which had to be solved using three different MEEs. Solutions found by the students have been documented and analyzed to identify system characteristics which enhance or inhibit the creative outcome.

Key words: Creative problem solving, technology education, mechatronic educational environments, Festo MecLab, Fischertechnik RoboTX, Lego Mindstorms EV3

Introduction

Human thinking and acting always takes place in a context. The context might be professional, cultural, private, public, disciplinary, interdisciplinary etc. In real life, this context is built out of many aspects. This paper refers to thinking and acting in technological contexts. This still reflects a wide field, which we will narrow down to technology learning in technology classes in comprehensive schools. In Germany in almost all federal states "automatization" is one of the core topics when it comes to curricula for technology classes. Learning within this school subject also incorporates thinking and acting in technology contexts and the use of typical technological methods.

Human thinking and acting on the other hand happens in spatial and social environments (Löw & Geier, 2014). For technology thinking and acting the environment includes technological artifacts like tools (real or virtual), machines, materials and other material objects. In context with industrial "automatization" these objects (e.g. industrial machinery) commonly are so complex that they are not suitable for pupils' learning activities or simply they come in sizes that do not fit into the classroom (Huettner, 2009). Therefore automation systems are available, which are especially designed for learning purposes in comprehensive schools' technology education. These systems are labeled differently depending on disciplinary and linguistic traditions. They are described as 'educational mediums', 'learning medium systems' or 'teaching environments'. Since most of these systems consist of mechanical elements combined with electronic components they are in this paper referred to as mechatronic educational environment (MEE).

In the described study we want to find out if MEEs with different components affect the creative problem solving of pupils. We also want to find out which components are more relevant than others and how they take effect on the pupils' action. To do this, we conducted a pilot study to check the research design and the testing process. We selected three similar MEE and gave them to comparable groups of students. These groups where all faced with the same problem which had to be solved in as many different ways as possible in limited given time with one of the three MEE. We captured the realized solutions and solution approaches and analyzed them to answer our research questions.

For reasoning our research approach and the study's design, we think it is necessary to discuss some findings of relevant scientific reference to outline the theoretical background. After pointing out the research task and relevant hypotheses, we outline the design of our study which was based upon those references. After a brief description of the implementation we will analyze and discuss the results of it against the background of our research questions.

Action

To reach basic needs like eating and drinking one must take actions (Funke, 2003). Psychology research points out that humans are self-determined and autonomous subjects that set themselves goals. Actions are means for reaching these goals. They are used deliberately and voluntarily. Acting can be divided into mental actions which take place internally only and do not affect the environment of a person directly and practical actions which cause interaction with the outer environment (Huettner 2005). For practical action the environment plays an important part. Options can be limited and interactive possibilities can be provided to support actions of individuals in that environment.

Problem solving

People prefer to rely on action sequences, recipes and algorithms which are represented in epistemic cognitive structures and are retrievable strategies for getting to a desired state (Edelmann & Wittman, 2012). If a goal cannot be reached by referring to such a ready-for-action strategy, the task becomes a problem. Problems are characterized by a current state, which one wants to turn to a desirable state. But in contrast to a task, no applicable strategy in the epistemic structure of mind is available. Instead the subject must construct a solution strategy by realizing, choosing and combining suitable action options. For doing this, humans make use of their heuristic cognitive structures. Indeed Heuristics are a kind of strategy, but they lead to the way of a solution instead of leading directly to the solution like algorithms do. Using such heuristics is rated to be one of the most important skills for successful problem solving (Kozbelt, Beghetto & Runco, 2010). Often, the three factors initial state, target state and the gap / barrier between those two are described as the constituting factors of a problem (Duncker, 1963; Luer & Spada, 1990; Fischer, Greiff & Funke. 2012). Edelmann and Wittmann devide the problem solving process into four phases (Edelmann & Wittmann, 2012):

Problem space

By reflecting the problem situation the problem solver creates a mental representation of the problem. This representation is of special meaning for a successful solution (Gerring & Zimbardo, 2008; Kozbelt, Beghetto & Runco, 2010). Knowledge of the problem context / environment impacts the representation as well as the experience of the barrier.

Situation analysis

In this phase, the problem solver reflects the difference between the current and the target state and clarifies what exactly has to be changed. Depending on the level of concretion and knowledge about this difference, the problem is more well-defined (available information and knowledge very specific) or ill-defined (less or no specific information and knowledge available) (Simon, 1973; Dörner, 1976; Urban, 2004).

Operator space

The amount of possible actions (referred to as operators) is the operator space. By selecting targeting and suitable operators, the extensive problem space has turned to a manageable operator space. The problem solver must have knowledge about this space, especially how the operators interact with the environmental states. Reducing the problem space by limiting the action possibilities and making the problem representation easier with additional media (e.g. visual mediums) can support the problem solution process.

Solution and evaluation

To verify if a found solution properly complies with the problem and if the target state is really achieved, the solution has to be implemented, tested and rated. If this verification checks out positive, the used solution strategy may be taken into the heuristic structures of mind permanently (learning).

Creative problem solving model (CPS)

There are some assessment tools aiming on problem solving. The CPS model which was developed by Osborn in the 1950s serves as a theoretical framework for practical creative problem solving. It divides the problem solving process in seven steps: orientation, preparation, analysis, hypothesis, incubation, synthesis and verification (Osborn, 1953). This model has been developed further to more advanced versions to meet upcoming needs. The current version consists of actions in three categories (understanding the challenge, generating ideas and preparing for action), between which one can switch any time according to one's appraisal (Isaksen & Treffinger, 2004). The CPS model does not reflect on the special environmental press of technology education though. This led to the need of developing an adapted model of creative problem solving we used as a basis of our study.

Harris lists seven important assessment tools with very different principles (Harris, 2016). Some observe people solving problems and rate their actions, others use classic questionnaires. Even a mixture of these methods is possible, for instance the creativity checklist CCh (Johnson, 1979). We will include these considerations into our design.

Complex problem solving

'Classic' problem solving uses quite simple problem scenarios for assessing data. This has been criticized as being not realistic because in real life people often are engaged in complex problems. Complexity has often been defined in literature differently since complexity became a focus of psychology in the 1970s (Funke, 2003). Researchers have been inspired by systems theory and began to understand problem situations as a system with according properties. Nowadays this discipline calls five properties to be relevant for characterization of a system (Funke, 2012): 1. Complexity: The amount of variables of a system is an important character of a system. The more variables a system has, the higher its complexity. *To deal with the high complexity the problem solver needs to simplify it by clustering variables and concentrate on the essential.* 2. Connectivity: Involved variables are not isolated from each other, but they interact. The more connections and interdependencies a system has, the higher is the connectivity. *The problem solver needs to have a sufficient representation of the connections.* 3. Dynamics: The interdependencies of variables as well as their states might change in accordance of time. So a system behavior can change though the users input to the system is the same. *The problem solver needs to adapt his knowledge about the system and consider the factor 'time'.* 4. Intransparency: Some variables or connections may be invisible or unknown. Even the goal of problem solving may be vague (ill-defined problem). *To engage intransparency, the problem solver must acquire needed information.* 5. Polytely: Acceptable goals can often be reached by more than one solution. Alternatives may be antagonistic, so *the problem solver needs to rate, make compromises and decisions*.

Different aspects have been researched about complex problem solving. In this context facing participants with virtual problem situations which have to be solved with a computer based model of a problem is very common. A feature of this setting is that the participants have realistic situations (as realistic as a computer simulation can be) without the need to have a real system and the effort that comes with it. Virtual systems can quite easily be programmed, even with a high grade of complexity, what is very appreciated by complex creativity researchers. Very famous is the 'Lohhausen'-experiment in which people had to act as a major of a simulated small city (Dörner, 1983). Another feature is that the character of simulated systems easily can be adapted by researchers (even at runtime) to observe the behavior of the participants. This makes it quite comfortable to test hypothesis.

Creative problem solving

Problems also can be an initial impulse for creative processes. Urban even points out, that problems always are the only reason for being creative (Urban, 2004). He assumes that problems must not just be specific questions / tasks with a fixed target state, but also diffuse ideas (ill-defined problems). Problem solving is inextricable woven with creativity and therefore it is a necessary skill for it (Dishke Hondze,l 2014; Dishke Hondzel & Gulliksen, 2015). "The autonomous detection of the problem is an aspect that separates creative thinking from pure problem solving." (Uhlmann, 1970, p. 23). The transformation of a problem to a solution seems to be analog. Early definitions of creativity already emphasized that creativity is connected to originality and novelty (Runco & Jaeger, 2012). Brander, Kompa and Peltzer (1989) described that creativity is used for problems, which trigger novel and original solutions. Because "creative thinking is just a special case of problem solving" (Johnson 1955 in Seiffge-Krenke, 1974, p. 14), one can examine creativity by observe the solution process of problems.

Since Guilford reactivated the interest in creativity research in 1950 there has been a lot of research actions. Though there is no standardized definition for the expression "creativity". Reviewing the researcher's work of the last 65 years, four important factors of creativity can be identified: the acting *person,* the creative *process*, the *press* (environment) and the product of the creative *process* (Rhodes, 1961, 1987; Krause, 1972; Runco, 2004; Kozbelt, Beghetto and Runco, 2010). These factors have been established in creativity research, that one can call it "the 'canonical' four Ps of creativity theory and research" (Glaveanu 2011, p. 7)

Some authors added further 'Ps'. For instance, Simonton suggested adding persuasion, because not just creative products have the potential to change the world; also the creators affect other people. For doing this, they must be recognized persuasively (Simonton, 1990). Though Runco picked this idea up and generated a hierarchic organized P-Modell that separates performances from potentials (Kozbelt, Beghetto & Runco, 2010), the four 'Ps' are currently still standard. So we refer to them in context with creativity as follows.

Person

Creativity is the result of individuals. By thinking and acting creatively they produce creative ideas and products. The decision of starting a creative process needs the person to be sensible and willing for situations, which needs the improvement of a creative action. A Person's abilities are affected by their traits. According to Guilford relevant for being creative are the traits of fluency, flexibility, elaboration and originality.

The person oriented research approach is focusing on person-inherent traits like genius, talent or giftedness. This approach assumes that the creative potential is mainly determined by the ability to think divergently. To measure it, manual tests have been developed. They were later on criticized for being artificial and not corresponding to real-life situations (Harris, 2016). Several tests were developed based on Guilford’s famous model of ‘Structure of Intellect’ (SOI), including the ‘Torrance Test of Creative Thinking’ (TTCT) (Torrance, 1966). Although the TTCT was developed in the 1960s, it has been a basis for creativity measuring to the present (e.g. Barbot, Besancon & Lubart, 2011; Dishke Hondzel & Gulliksen, 2015)

Process

The creative process can be divided into different stages. For instance, Torrance gave a famous stage-based definition. He defined creativity as a process of sensing gaps or missing elements, forming ideas and hypotheses, concerning them, testing these hypotheses, communicating the results and possibly modifying and retesting the hypotheses (Torrance, 1962). Often the four stages of Poincaré are referenced: The creative process must begin with a preparation stage, when the problem or situation is analyzed by thinking consciously. The following incubation stage is a period of resting, in which the mind focuses on other activities. The following illumination stage occurs, when the key-idea occurs suddenly. Poincaré describes this stage as the result of unconscious prior work. This idea is not the final solution; it is more like a way that leads to it. So the illumination must be further developed from “raw format” to the concrete goal in the stage of verification, which means conscious work again (Poincare, 1913).

In this process, two ways of thinking are necessary: In the conscious stages especially convergent thinking skills are important: for analyzing, calculating, data collecting and deciding the thinking must be focused on the goal. This kind of thinking is structured and logical. Divergent thinking cannot be structured or even described. It happens merely unconsciously and cannot be planed or calculated. By thinking divergent persons can find new approaches that have not been constructed systematically of existing knowledge.

The innovation process is controlled and done by persons, so the oriented approach still tries to measure traits and attitudes of persons. Unlike the person oriented approach, it opens to attributes which take place in the active process of creative thinking (Harris, 2016). Even though this approach had peaked in the 1970s, it still is a source for modern tests (e.g. Beghetto, 2006).

Product

The result of the creative process can be a material or immaterial product. It must be suitable to the situation or problem, which is initial for a creative process. It makes a big difference if one is creative in contexts with more subjective criteria (e.g. arts like music, painting, writing) or in more objective contexts like technology or sciences (Wegerif, 2010). Though the creative process itself seems to work equally in both, the reason and occasion for being creative and the evaluation criteria for the suitability of the product is very different.

Assessment of creativity in accordance to the product-oriented approach concentrates on the analysis of the product of a person thinking and acting creatively. For getting these products, participants are faced with a task that includes the realization of a product (e.g. a drawing or a story). Because of this and due to the product being the final of a creative process and being ‘located at the end’ of this process, one can assume that all the other ‘Ps’ are involved in the product. However, they are not ‘visible’ in the product and cannot be extracted for drawing conclusions on the process of creation. This approach therefore has been criticized for facing participants with artificial tasks (Barbot, Besancon & Lubart, 2011; Harris, 2016). The Student Product Assessment Form SPAF for example is available for education contexts, which helps rating creative products of students based on nine factors, e.g. problem focus, diversity of resources, audience (Renzulli & Reis, 1997).

Press (or place, pressure, environment)

Another relevant factor is environment, in which the creative process is embedded. On the one hand, it must deliver a situation (or problem), which can be detected by an individual and be interpreted as an initial event for being creative. On the other hand, the environment rates the product of the process and decides about its suitability. The process has been successful, if the product is accepted by the environment. Further on, the environment delivers possibilities and restrains for creative problem solving actions. This includes the physical environment as well as the social and cultural environment. All these entities put pressure to the creative problem solver.

In research, this approach has two focusses (Ryhammer & Brolin, 1999). On the one hand there is the socio-cultural understanding of environment, which measures the impacts of society and culture on creative processes. This focus takes static aspects into account that affect the creative individuals and processes from the outer environment like culture, biography, parents, childhood etc. (e.g. Dishke Hondzel & Gulliksen, 2015). On the other hand a creative process incorporates many social events. Individuals interact with other persons as well as with the physical objects in the surrounding space (Amabile, 1996; Elisondo, 2016; Lebuda, Glaveanu & Galewska-Kustra, 2016). Although this approach offers various research perspectives, there is not much environmental research (Galewska-Kustra, 2016) or assessments (Davies, Jindal-Snape, Collier, Digby, Hay & Howe, 2013). Harris points out that those environmental dimensions of creativity are often overlooked by research and assessment though education can benefit from this research approach (Harris, 2016). At least, there is some research on creativity in education (e.g. Plucker, Beghetto & Dow, 2004; Tracey, 2011).

Conclusions for the assessment of creative problem solving in technology classes

Creativity can be assumed as a key factor for the development of a civilization. One of the major aims of education is to evolve the ability to solve problems by thinking and acting creatively (Hennessy & Amabile 2010; Gralewski, 2016). According to Beghetto three forms of creativity teaching can be devided (Beghetto, 2017): First teaching about creativity which means to enhance students' awareness of creativity, its theories and its understanding. Second, teaching someone to be creative by training relevant skills, for instance by training creative methods. And third, using creativity within the teaching itself as a didactic principle.

Technology provides a lot of innovations which have impacts on society and culture. As a final oriented discipline, the domain 'technology' is aimed for developing, producing and using new ideas and products. Thus, being creative and solving problems is an integrative part of the huge domain of technology. Technological products are not natural but artificial. So dealing with artefacts and creating them is the 'nature' of technology. This makes the above mentioned third form of using creativity within the teaching process to a native teaching method in technology education. In our opinion this predestines technology as a domain for creativity research. According to our study that is why facing students with a problem in a technological context should not be perceived as too artificial.

A finding of reviewing creativity research that has to be focused more in detail is 'novelty'. For Ghiselin, the novelty is always unique, the same product cannot be novel twice: "A creative product is a mental configuration; it … is unique at the moment of mental birth in a way, that there are no specific predecessors." (Seiffge-Kernke 1974, p. 13). Many definitions of creativity demand an original and novel product (Runco, 2003; Barbot, Besançon & Lubart, 2015). Some definitions also include, that the novelty is considered by a specific group (Amabile 1996; Runco, 2009). Considering that novelty is no absolute expression because "a creative product can be new for a single person, new for a group or new for a society" (Hüttner, 2005 p. 5), creativity is also relative due to novelty being obligatory included in creativity. This is a very important recognition for researching the creativity of children, for instance in education contexts.

The acceptance of the creative product of the members of a domain is a criteria, that can be divided into two different specifications (Plucker & Beghetto, 2004): If a creative product effects a domain like a huge group of people in the dimension of a big community, a society or a public market, it is a result of the 'big C' creativity. The aim of this kind of creativity can have sustainable effects on a huge amount of people. If a creative product has an essential impact on a domain in the dimension of a culture or a big society, it is also called 'eminent creativity' or 'historical creativity'. This extreme form of creativity is very rare and just a few people are able to do it. Insisting on this approach would mean that creativity could just be done by a small amount of gifted experts, excluding children (Sawyer 2003). That is why 'little C' approach has been established. The aim of 'little C' processes is to satisfy an individual need, so the impact is also limited on the individual person or small group. Corresponding products are useful and accepted by a limited group of persons or even a single person. It occurs in daily life, so it is also called 'mundane creativity' or 'everyday creativity'. Fortunately, for research it is opportune to transfer 'little C' creativity findings to general creativity abilities, including 'big C' creativity (Westmeyer, 2009). Without this assumption, most creativity tests could not deliver applicable results.

There is a big gap between little and 'big C'. Not anyone will reach the level of 'big C', because their products are not outstanding enough. Though they have been creative on a higher level than 'little C'. For instance, people write songs that are famous on a regional level but never get famous on a global level. It is obvious that this is not just a mundane level on the one hand and not 'big C' level yet on the other hand. Between these two levels, the 'four C model of creativity' inserts the 'pro C' level to fill this gap (Kaufman & Beghetto, 2009).

The model also describes creativity on a 'mini C' level. This level is used when people are creative while learning. The aimed for product is not a classic product of the creative process, but the learning of knowledge and skills. Without referring this level, learning itself could not be considered as creative. For educational creativity research we think this approach is very useful. Our study aims on learning environments designed for and used in teaching and learning scenarios. The products students create with it will probably not meet the standards of 'little C'. Due to that we believe that the 'little C' approach is very important for justifying the general idea of the study's design, where the participants solved problems with the exclusive help of different MEEs creatively.

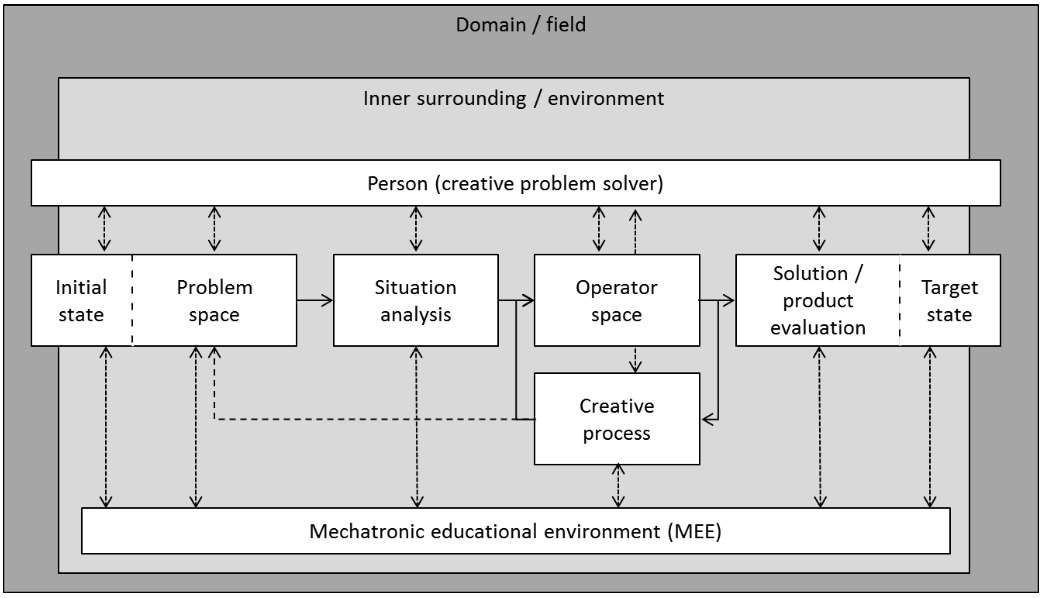

Figure 1: Model of creative problem solving with MEE.

As already mentioned above, problem solving and creativity have many things in common. An encountered problem may initialize a creative process that delivers a creative product as solution. Thus one can combine the above discussed findings of problem solving and creativity to create a suitable model of creative problem solving within the domain of technology.

The problem solving with its described states (initial and target) and the four parts formulated by Edelmann and Wittman (see above) is one of the central elements. As mentioned already, it can be assumed that persons try to use their available strategies (epistemic structures of mind) and heuristics (heuristic structures) first to find a matching solution. If a solution cannot be found this way, people have to create new ideas by running a creative process. Generated ideas are evaluated (operator space) and lead to a solution / target state or, if insufficient, to another creative process. Creative thinking may also cause changes in the representation of the problem (problem space). All these steps cannot happen without the person being active. Due to that, the person (and her/his traits) takes effect on all other steps. All this is not just happening in an isolated, but in a surrounding space. Parts of this space are other people as well as physical objects and material resources. Both are expected to have relevant influence on the problem solving process (Galewska-Kustra, 2016; Gralewski, 2016; Davies et al. 2013). We differentiate the surrounding space from the domain / field. This would be more of a content-related frame, which delivers the problem situation and evaluates the solution.

In our study, we focus on a special part of the surrounding space, which has domain specific concretions and must be explained a bit further. Compared to other disciplines, technology education requires the use of a large width of specific educational environments: descriptive representation forms (like texts, drawings, video and audio) is used by all disciplines, but physical, specific forms ('things' like real models and objects) are not (Schmayl, 2009). Though technology is not the only discipline that includes practical processes in its education, the implementation of 'things' like tools, machines, models and materials is very specific for technology classrooms. This enables students in technology classes not just to learn via symbolic or iconic represented information, but to learn enactively by operating with real objects.

When practicing creative problem solving in the domain of technology, the available educational environments become very important due to the restraints and options they bring with them. A special characteristic of technology according to design and production process is the duality of available (production) materials. On the one hand, these materials deliver restraints and features to the solution process (like any other environment does). On the other hand, these materials also represent the solution / product after finishing the solution process. This makes us assuming that the importance of physical represented material is emphasized in technology problem solving processes. That is why we focus on this form of environments.

Numerous researches can be found about the environmental influences on creativity (e.g. Cropley 1992; Amabile 1996; Craft, 2001). Available tests measure socio-environmental factors aiming more on cultural or organizational aspects (Amabile 1995; Eyseneck 1996; Forbes & Domm, 2004). There are no domain specific tests for technology though, which could be used for measuring the influence of MEEs. Anyhow, Davies et al. identified seven studies in the context of "learning abilities involving the making of artefacts" (Davies et al. 2013, p. 84) and extracted strong evidence that providing a wide range of appropriate materials, tools and other resources can stimulate creativity. We adapted this finding and concretized it for better matching MEEs. The amount and diversity of sensors for detecting states and actors for manipulating the environment is equivalent to a wide range of material. MEEs with less different sensors and actuators are expected to support creativity less than systems with more. Creative solution processes are also affected by the mechanical hardware of a MEE. The flexibility of mechanical components leads to more or to fewer various solutions and solution ideas. This way, the mechanical flexibility can be seen as equivalent to the range of materials also. This leads to the following, more specific research questions:

- What kind of components of MEEs are of particular relevance for the creative problem solving process?
- To what extent does the available amount of different sensors and actuators determine the creative problem solving process?
- To what extent does the technological context affect the creative problem solving process?

To find answers for these specific questions we formulate three hypotheses, which will be examined in our study:

- H1: More available sensors and actuators of MEEs enhance the creative problem solving process.
- H2: MEEs that have more specific (non-universal) components inhibit the creative problem solving process.
- H3: People prefer to make use of components whose intended purpose is directly connected to the given technological context when solving problems in such contexts.

Design of the pilot study

Due to the environments in which we are interested in are not just corresponding with the press but also represent the product, one can also assess the product for getting information about the creativity of the product. This approach seems to match to technology context perfectly, because the creation of a product is an immanent way of technological thinking and acting and influences the culture technology as a discipline very much. Though focusing on the final results of a creative problem solving process would be and approbate method according to the specific domain, particularly because authors emphasize the domain specificity of creativity (Baumert, 1996; Runco & Pritzker, 1999; Plucker, 2000; Baer, 2016). Unfortunately, no technology specific assessments are available. Even a limited overlap between product-based measures in different domains has been found (Lubart & Sternberg, 1995). We ourselves decided not to develop a measurement tool based on the rating of domain experts like others do. Instead we faced the learners with a single problem and told them to develop as many different solutions for this problem as possible in a limited amount of time. To raise the events of finishing solutions successfully, we designed a problem that consists of three separate problems that have to be solved and combined to engage the complete problem. By capturing the realized solutions for the three separate problems in accordance to time and by also recording not realized solution ideas (potential solutions), it should be possible to draw conclusions of the person's creative problem solution process. We believe that this way of assessing data meets the demand for mixture of methods in measuring to avoid a deficient approach limited on one single 'C' of creativity (Glaveanu, 2010). Due to the participants had to realize the solutions exclusively with one of three MEEs, the press the given MEE caused, is integral part of the solutions / products.

The three utilized MEEs consist of construction parts that can be combined in uncountable ways to get the wanted construction. The given sensors enable the participants to make their solution sensible of several events and states. The given actuators offer many different ways to interact with the environment. Functional connections between environmental states and actions are programmed by the user via software. The software also allows a huge amount of variations for connecting events and actions and for determining the solutions' behavior. It is of no question that the participants have to deal with complex problems and complex environments. To reduce the impact of complexity, we trained the participants to operate the MEEs and to raise the knowledge of them. The introduction did not include solution principles that could directly be used to get a (partly) solution. We also gave support during the problem solution process by coaching and helping the participants in the operation of the MEEs, but not in finding solutions. This way we wanted to shorten the long time it needs to learn operating the MEEs and avoid obstacles caused just by operational problems.

To get some information about the creative abilities of a person, Guilford developed a famous structure of intellect which identified more than 120 traits (Guilford, 1967). Based on this structure he developed a lot of tests, even for measuring creativity. Maybe one of the most famous of tests on this basis is the Torrance Test of Creative Thinking (TTCT), which assesses creative thinking in form of words and in form of pictures (Torrance, 1966; Torrance, 1998). The verbal part includes the 'Brick Uses Test', which tells the test persons to find as much use options for a brick as possible in 10 minutes.

Our study design is based on the idea of the 'Brick Uses Test': Due to the timely proximity to the "European Soccer Championship", we created a problem called "11 cm penalty shootout". We told the participants to construct as many machines as they can in 140 minutes that can realize the following functions:

- A wooden ball or a marble (diameter of 2 cm) must be transported into a goal (5x5 cm) from a distance of 11 cm.
- The successful goal-shoot must be detected by the machine.
- A successful goal-shoot must be signaled by the machine.

This problem must be solved with one of three MEEs, which are described in the following chapter. We separated the pupils in different groups of two or three participants and allocated one MEE to each group.

As already mentioned, we are describing a pilot, not the final study. We aim to test more participants in the final study so that the personal traits would be distributed evenly according to the three MEEs. Due to this we expect that the MEEs are the only 'variable' that is differentiating between the groups.

As indicated in above, we divided the problem into three sub-problems: *the transportation of the ball, the detection of the goal and the signal that reports the goal.*

Any construction had to shoot three goals in a row to check the reliability. All solutions, which passed this check, have been counted. A solution was accepted as novel, if one of the three demanded functions used a new function principle. This way, we raised the amount of creative problem solving events, which increases the generated data. We captured any realized solution for each sub-problem, solution idea and aborted solution approach and the time they occurred.

Introduction to the mechatronic learning environments

In the process of developing the described pilot we decided to concentrate on three MEEs: *Lego Mindstorms (EV3), Fischertechnik RoboTX and Festo MecLab.*The decision was made due to the fact that German technology classrooms are if at all commonly equipped with one or more of exactly those MEEs.

Following the above mentioned findings of Davies et al. (2013) that providing a wide range of appropriate materials, tools and other resources can stimulate creativity we assumed that the flexibility and the comprehensive delivery scopes (in context with tools and materials) of all three MEEs provide what is needed to nurture the pupils' creativity.

When taking a closer look to what is provided out of the box by all three MEEs one can find major similarities between them but also some significant differences. Both will be described below.

The first thing to mention is that all three MEEs can be divided into four functional classes as follows:

- Construction elements, consisting of structural/static elements and fastening elements, used for constructing or building technological models and/or housing sensors and/or actuators,
- A controller with input-ports and output-ports and some kind of control panel, designated to read data from sensors and to control actuators, used to interconnect both in a flexibly selectable way,
- A software, used to write programs which can be stored and run on the controller to make use of the data provided by the sensors and/or make the actuators do something (influenced by the data or not).
- Sensors and actuators, used to read environmental data and let the MEE do something (e.g. movement or signaling),

We assumed that these similarities alone would make them comparable to each other hence it would be possible solve the above developed problem with any of the above mention systems. The differences of the MEEs can be revealed by examining them more thoroughly in context of the above mentioned functional classes.

Construction elements:

In all three cases the user is provided with a large amount of construction elements and fastening elements.

- Lego EV3: The basic set consists of the assumed to as known constructional elements of the “Lego” an “Lego Technic” systems. It is fully compatible to the “Lego” brick system. All parts can be interconnected mainly by interlocking or by friction locking leading to relatively strong constructions. Building blocks can mostly only be connected within a certain grid dimension.
- Fischertechnik RoboTX: The main component of the Fischertechnik system is a cuboid shaped building block equipped with tongues and grooves on all six sides. As with Lego the interconnections between blocks, cogs and axis are mainly by interlocking or by friction locking. Although there is some kind of grid dimensioning with Fischertechnik too, the building blocks are a little bit more flexible because the tongues and grooves provide the user with the possibility to slide some parts in a continuously variable way.
- Festo MecLab: The Festo MecLab comes with metal construction elements in default shapes and structures. These can be interconnected and combined with bolts and nuts. There is no specific grid dimensioning at all as the parts come with predefined fastening points. As the system has a stationary design it comes with a mandatory building base to which all elements are fastend. There is some flexibilty in that because the buildingplate uses sliding nuts which can be positioned anywhere in grooves that run along the whole building base.

Lego and Fischertechnik additionally provide the user with various axles cogs and fastening elements to fit the parts together or transfer movements.

Controller:

- Lego EV3: The controller provides four ports to attach sensors and four ports to attach actuators. Additionally the buttons and the led-lights built into the controller can be programed to be used as actuators respectively sensors (e.g. for signaling or triggering events). The built-in display itself and the speaker are also programmable. All parts are connected by the user via encoded data cables that deliver power and/or transport data between the components. They are securely fitted with special cable connectors.
- Fischertechnik RoboTX: The controller provides eight ports to attach sensors and eight ports to attach actuators. In addition to that there are four digital counting input ports. All parts of the system are connected via simple insulated wires to which the user has to attach small connectors in order to plug them into the components. These cables deliver power and/or transport data between the components.
- Festo MecLab: The “MecLab” can be controlled by various controllers. We used a version which came equipped with the “Logo!” controller by “Siemens”. The “Logo!” Controller is attached to the original wire distribution terminal from Festo. This is summing up to six input ports to attach sensors and six output ports to attach actuators. All parts are connected by the user via encoded data cables that deliver power and/or transport data between the components. They are secured by screw fixings.

Software:

All three MEEs provide a simple yet powerful software solution which should be easy-to-use for pupils when trained.

- Lego EV3: The software used for programming the EV-3 in its latest edition is based on merely pictographic programing blocks that can be combined by simple drag-and-drop actions. The flow of the program can be altered by dragging lines between the different programming blocks. Some multitasking can be achieved by dragging lines from one starting point to more than one adjacent program sequences. Data can be exchanged between programming blocks by drawing/dragging lines between blocks’ input and output docking points.
- Fischertechnik RoboTX: For programming the controller the “Robo-Pro” software is used. The program flow is mostly visualized pictographically by programming blocks that can be applied to a program sequence by simple dragging-and-dropping actions. Lines can be drawn between each block to provide a flow sequence or for exchanging data between programming blocks.
- Festo MecLab: As above mentioned we are using the “Siemens Logo!”-controller to control the MecLab which is why we use the “Logo!Soft” solution to program the controller. Programs are like in the other two MEEa created by simple dragging-and-dropping actions combining programming blocks in sequences and drawing lines between them. These are visualized according to the industrial ‘Function Block Diagram’ (FBD).

Sensors and Actuators:

- Lego EV3: Comes with ultrasonic sensors, gyro sensors, color sensors, touch sensors and medium or large servo motors.
- Fischertechnik RoboTX: Comes with infrared trail sensors, phototransistors, push-buttons, XS motors, encoder motors, adjustable gearboxes and lamps. Also a light-barrier can be established by combining a Lamp with a phototransistor.

- Festo MecLab: Comes with light barrier, inductive sensor, stopper/deflector, mono- and bistable solenoid valves, stamping units, double acting cylinders and various compressed air distributors, switches and valves.

In conclusion we found that the three systems are very similar when it comes to construction elements, software and controller but do mainly differ in the provided sensors and actuators being compared against the background of the problem given to the pupils. By simply counting the sensors and actuators provided in basic configuration we came to the following ranking between the systems:

Table 1: Type and number of sensors and actuators included in basic configuration of each MEE.

1. Lego Mindstorms EV3		**2. Fischertechnik RoboTX**		**3. Festo MecLab**	
Sensors	Actuators	Sensors	Actuators	Sensors	Actuators
1x Ultrasonic sensor 1x Gyro Sensor 1x Color Sensor 2x Touch Sensor 6x Buttons	1x Medium motor 2x Large motor 1x LED-light 1x Speaker 1x Display	1x Infrared trail sensor 1x Phototransistor 2x Push button	2x Encoder motors 1x XS motor 3x Lamps	1x Inductive sensor 1x Light Barrier	1x Conveyor belt 1x Solenoid 4x Cylinders 1x Pneumatic gripper (1x LED light)*
Σ: 11	**Σ: 6**	**Σ: 4**	**Σ: 6**	**Σ: 2**	**Σ: 7 (8)**

**: The LED light is built into the light barrier and thus is not an actual actuator. It can be used for signaling an event though (and was through the trial).*

Due to the fact that they serve as an interface between the machine and/or system and its surrounding the available sensors and actuators have large effects on the possibilities the MEEs provide to the user to solve the given problem. This led according to Davies et al. (2013) to the assumption that the system which provides the highest amount of “tools and material” on the background of sensors and actuators will also lead to more solutions when used to solve a given problem and vice versa that the systems with fewer sensors and actuators will lead to fewer solutions to the given problem.

Preparations and Limitations

Although we found the three MEEs to be very similar (except in context with provided sensors and actuators) at this point some major differences showed up between the MEEs. While the “Lego Mindstorms” and the “Fischertechnik RoboTX” systems are construction kits from the scratch the “Festo MecLab” system comes in three ready-to-use built components:

- Stack magazine station
- Conveyor station
- Handling station

So to make it comparable to the other MEEs the “Festo MecLab” had to be disassembled and prepared to be used as a construction kit. This caused some issues with the scope of delivery. For example there were not enough fixing brackets and compressed air distributors per single set. Therefore we developed a unique construction kit based on the “Festo-MecLab” system. Part of this development was the addition of some screws and constructive parts from a “Märklin” metal building kit and the development of a few completely new fixing brackets both being added to the original set. All alterations have been made very carefully as to not change the characteristics of the “Festo MecLab” too much. It is important to acknowledge though that with the given problem this was the only way to compare the “Festo-MecLab” to its competitors.

Training

Since the test participants were going to work for the first time with their dedicated MEE there had to be some training to make them able to fulfill the given task. Within this training which lasted exactly 60 minutes participants learned basic skills about construction elements, fastening and mounting elements, actuators, sensors, wiring and programming of the respective MEE. Training procedures were developed and tested against each other group so that they became as comparable as possible. Furthermore for each MEE there was developed a reference card with basic (and also some advanced) information about all important components. These cards where to be handed to the participants to help them remember significant information mainly about actuators, sensors and programming.

The training was developed towards the target that the participants would get no hint or targeted assistance in solving the given task by the conductors. There have been some elements in each training (e.g. a lever that was turned by a motor or a vehicle that runs on a track) that could have inspired some of the ideas the pupils later implemented within their solutions though.

Scheduling

Given the fact that the training and the initial survey were vital elements in the following course of the trial they had to be scheduled first in line of testing.

This reduced the available timeframe for the participants to work at their solutions from four hours to about two and a half hours (60 minutes training and 20 minutes initial survey prior to that plus some extra minutes for organizational issues).

An additional 10-minute break in the middle of the working progress decreased the available working time to 140 minutes (or two sessions of 75 minutes). The conductors performed an interview every 20 minutes which added up to six or seven interviews in total.

Problems were encountered when realizing that the available pupils had due to public transportation matters only 200 minutes. Training and initial survey were compressed into a tighter timeframe (15 minutes for the survey, 45 minutes for the initial training) so that there still was a total of 140 minutes of working time divided into two sessions of about 65-70 minutes each.

Documentation

As stated above part of the measurement of possible creativity outcome related to each MEE was to record all solutions found by the participants working with respective MEE as accurate as possible. For this purpose we developed forms with which the conductors were able to record every solution the participants found separately. The recordings included a timestamp and a short description or drawing of the solution found by participants. – The solutions were recorded according to the above mentioned sub-problems “transportation”, “detection” and “signaling”.

As mentioned above there was a significant possibility that the participants were not able to actually build every solution that might have come to their minds. Therefore the conductors had been requested to interrupt the participants within their working progress periodically to ask some interview questions regarding planned solutions and possible ideas that had come to mind but were not yet practically realized. The answers were written down (or drawn) by the conductors into the same forms and counted as found solution.

Additionally a short questionnaire has been distributed and evaluated directly prior to the main part of trial. The results of said questionnaire were used for further classification of the results recorded in the main trial. Participants were questioned about their attitude towards technology and technology education, about their knowledge of the given MEE and asked details about their age and gender. Especially the results regarding the knowledge of a specific MEE led to the assignment of the pupils to one of the systems. We made sure that the pupils only worked with system they had said in the questionnaire to have little to no knowledge of.

Test Run

To initially test the complete trial design including hard- and software setup as well as the initial survey and the documentation methods a test run has been conducted prior to the actual trial. For this test run ten students who did not have any experiences with one or more of the MEEs have been randomly selected. The test run showed that the preparation of the hardware and the training were expedient. There had to be made some small alterations to the forms used for documenting the solutions found by the test participants though. This was in order to give the conductors more space to write down information given to them in the interviews. The scheduling was also found to fit the purpose.

Test Groups and Implementation

The test has been implemented in July 2016 with 33 ninth graders from a school in proximity to our facilities. The above mentioned questionnaire helped to divide the pupils into smaller groups while assuring that no test participant was going to work with an MEE he or she had any prior knowledge of.

To make the results more comparable and reliable it was planned that there should have been four groups working parallel for every MEE available. We did not interchange the groups between the MEE because that would have meant that the pupils had the chance to use their experiences with the given problem in context with one MEE to find solutions with another system faster.

Due to the above mentioned fact that the “Festo MecLab” had to be altered, all the onsite available sets had been merged into just one construction kit. Therefore we had to address to some differences within the group composition when testing the MEE with actual pupils. Since every session of the experiment took exact four hours and the pupils were only available in the forenoon of one day only one group was able to use the “Festo-MecLab” per day. To adjust the size of the experimental group between all MEEs the experiment was repeated with the “MecLab” on four further days. In the end the mentioned group of 33 pupils has been divided in four groups using “Lego Mindstorms”, four groups using “Fischertechnik RoboTX” and four groups using “Festo MecLab” to solve the given problem.

Statistical Data

The main focus of this trial was to find an answer to how the provided scope of sensors and actuators of three specific MEEs influences the number of found solutions for a specific problem. The initial questionnaire brought up some interesting “side-facts” though so that this section is concentrating on the results of said questionnaire before switching to the results of the main trial.

Participants:

All participants where ninth graders and came from different classes of the same school. The average age of the pupils was 15.24 years (M=15; SD=0.50),14 where male and 23 where female.

Knowledge of the different MEE:

A four point Likert-type scale was used to classify the participants’ knowledge of the different MEEs. The four items of the scale ranged from “I don’t know it at all” (1 point) to “I have profound knowledge and I am playing/working with it frequently” (4 points).

The results in this context were mostly as expected. The “RoboTX”-system and the “MecLab” have from a viewpoint of personal observation not reached a wide distribution among German comprehensive schools. It is not surprising that pupils mostly checked at the “lower end” of the scale and thus expressed that they did not know anything of said MEE. The knowledge of the “RoboTX” reached an average of 1.06 (SD=0.24) and the “MecLab” an average of 1.18 (SD=0.46).

There was one exception with the “Mindstorms”-system though. The school our participants came from is well equipped with the “Mindstorms”-system and can offer in average 2 courses per grade level, what is a lot compared to most other schools. In spite of that the pupils rated their knowledge of the system with an average of 1.57 (SD= 0.79). It is now possible to say that most of the participants had little to no knowledge of the given MEE.

Usage environment:

Even more interesting are the results which indicate where the participants mostly had contact with the MEE. With this item they were able to choose between “at home”, “at school” or neither of both. Only one participant specified that he had used the “RoboTX”-system in school. All other participants specified that they have used the system neither at home nor at school. With the “MecLab”-system all participants specified that they have not used the system at home or at school. Finally participants reported that they have used the “Mindstorms”-system mostly at school when they had used it at all. One female participant though had used the system at home. This leads to the presumption that teenagers make most of the experiences with MEEs at school, if at all.

Interest in technology and technology careers

Since technology education is not wide spread in Germany and in some federal states on the verge of extinction it was interesting to question the participants about their attitude against technology and a technology related career.

It is important to understand that in the federal state of Schleswig-Holstein where the participants came from, technology classes are very popular with the pupils and wide spread so that the development of technology education in this state is opposing to other states. For all questions the pupils were presented with a Likert-type scale of 6 points. The first question addressed to the pupils interest in technology education at school. They reported with an average of 2.93 (SD=1.00) which states that they are not decided or the opinion within the group divides.

The second question to the participants was about how often they use technology in their daily lives. The pupils reported with an unexpected average of 2.03 (SD=1.02) to this question which means they do not use technology as often in their everyday lives as expected. This leads to the cautious interpretation that the pupils questioned had a very narrow sight on technology and do not recognize all technology they are using everyday as such. The third question asked about the pupils’ interest in the functionality of technological artefacts. An average of 2.64 (SD=0.96) with that question shows a wide spectrum of interest or lack of interest. Because of the poor evidence provided by the results of the second and third question the results will be addressed later for a closer gender related revision. The fourth question asked about the pupils’ interest in a technology related career. With an average of 3.81 (SD=1.31) over half of the pupils stated that they would not consider a technology related career at all.

At the end of the survey two questions about technology related hobbies and if the pupils had technology classes in school at all where asked. With an average of 1.81 (SD=0.46) the pupils merely reported that they do not have a hobby which includes the usage of or is related to technology. This strengthens the position that the participating pupils had a merely narrow view on technology as they mostly did not connect their hobbies to technology (e.g. “composing Hip-Hop music” was not connected with technology). The majority of the participants though has been participating at least in one technology class with average of 1.45 (SD=0.51) classes. *At this point a gender related revision of the last few questions makes sense:*

Table 2: Found solution principles for MecLab.

Question	mode	average female (SD)	average male (SD)
How important is it to you to learn something about technology in school?	1=important to 6=not important	2.89 (1.15)	3 (0.78)
How often are you using technology in your everyday live?	1=very often to 6=rarely	1.89 (0.99)	2.21 (1.05)
Are you interested in the functionality of technological artefacts?	1=very to 6=not at all	2.26 (0.87)	3.14 (0.86)
Are interested in taking on a technology related career?	1=very to 6=not at all	3.47 (1.38)	4.29 (1.06)
Do you have a hobby related to technology?	1=yes 2=no	1.79 (0.42)	1.86 (0.53)
Have you ever participated in a technology class in school?	1=yes 2=no	1.31 (0.48)	1.64 (0.50)

The insignificant difference in the answers between male and female participants possibly points to the fact that gender related differences in the attitude or interest in technology had no part in the results of the initial survey.

Results

For compiling results out of the captured data it seems to be appropriate to focus on the analysis of the quantity of found solutions and check the correlation to the amount of realized solutions. The Pearson-correlation between the quantity of sensors and actuators and the found solutions is $r = 0.67$. Due to the low number of cases in this pilot this result should not be overestimated. Some more detailed analysis of data is showing further results. Table 3 lists the quantities of sensors and actuators per MEE and compares them to the amount of found solutions. Comparing these figures shows that MecLab and Mindstorms produced nearly the same amount of solutions though MecLab has much less sensors and actuators (S&A) and RoboTX supports less solutions with the same amount of sensors and actuators than MecLab does. Calculating the quotient q_1 (solutions / S&A) shows the 'performance' of each MEE.

Table 3: Quantity of sensors and actuators and solutions.

MEE	Quantity of sensors and actuators (S&A)	Founded solutions	q_1 (solutions / S&A)
Festo MecLab	10	41	4,1
Fischertechnik RoboTX	10	34	3,4
Lego Mindstorms EV3	17	43	2,5

As already mentioned the novelty of a solution is an important property of a product generated creatively. We already described that in educational context novelty must be understood relatively to each participating learner. Table 3 has been generated under this requirement. Additionally the creative products can be analyzed relatively to the MEE. In this case, solutions found repeatedly by different participants could not be rated as novel. Due to that table 4 bases on different solutions exclusively and shows that Lego Mindstorms EV3 performs significantly weaker in creative problem solving compared to other two MEEs. It also shows the 'differentiating performance' q_2.

Table 4: Quantity of sensors and actuators and different solutions.

MEE	Quantity of sensors and actuators (S&A)	Different solutions	q_2 (different solutions / S&A)
Festo MecLab	10	20	2,00
Fischertechnik RoboTX	10	21	2,10
Lego Mindstorms EV3	17	20	1,18

To explain the variation of the 'differentiating performance', a closer look to some qualitative details is helpful. For this purpose the tables 5, 6 and 7 display the various solution ideas separated by sub-problem separately for each of the three MEEs. We used shortcuts 'S' and 'A' to indicate if an actuator or sensor is involved. 'M' indicates that the solution idea is based on mechanics and doesn't involve S&A.

Table 5: Found solution principles for MecLab.

Signaling	Detecting	Transporting
A: Sensor-integrated LED lights up A: Lifting magnet extends A: Throttle valve blows a second ball A: Cylinder extends A: Solenoid blows air A: Throttle valve blows air	S: Ball rolls through light barrier S: Ball moves metal plate that activates inductive sensor	A: Throttle valve blows ball A: Conveyor belt moves ball M: Ball falls down from a platform A: Gripper arm places ball M: Ramp accelerates ball A: Cylinder bumps ball M: Marble bumps ball A: Airstream deflects ball M: Railing deflects ball A: Cylinder bumps marble M: Ski jump accelerates ball A: Gripper kicks ball

Table 6: Found solution principles for RoboTX.

Signaling	Detecting	Transporting
A: Lamp lights up A: Lamp blinks A: Motor starts (makes noise) A: Linear motor moves pointer A: Motor with propeller generates airstream M: Object falls over	S: Ball rolls through light barrier S: Push button is activated by ball	A: Motor with lever kicks ball A: Motor with propeller kicks ball A: 2 motors with 2 wheels squeeze and shoot ball M: Ramp accelerates ball A: Motor with paddle wheel pushes ball A: Linear motor pushes ball A: Linear motor pushes marble M: Ramp accelerates marble M: Marble bumps ball A: Propeller blows ball A: Motor with crank kicks ball A: Motor with 1 wheel squeezes and shoots ball A: Elevator (with linear motor) places ball on ramp

Table 7: Found solution principles for Mindstorms.

Signaling	Detecting	Transporting
A: Playing sound A: LED (in brick) blinks A: Motor (transport) stops A: Motor with propeller blows A: LED (in Brick) changes color A: Additional Motor starts (makes noise) A: LED (in Brick) lights A: Vehicle starts moving	S: Color sensor detects ball S: Supersonic sensor detects ball S: Push-button is activated by ball	A: Motor with lever kicks ball A: Vehicle accelerates ball M: Ball strikes another ball A: Belt conveyor transports ball A: Motor with lever releases ball M: Ramp accelerates ball A: Motor with arm throws ball (catapult) A: Picker arm moves ball M: Ball falls from platform

Some ideas seem to be very similar (e.g. ‘Lamp lights up’ and ‘Lamp blinks’). Nevertheless we interpreted them as different, because there is a difference in the programing. Ideas like ‘motor with lever kicks ball’ and ‘motor with propeller kicks ball’ look equal too, but it is a significant mechanical difference to use an out-of-the-box part (propeller) or to construct and build a lever, that is made especially for this task. Changing the input port has not been rated a new idea (and nobody has tried to increase the solution quantity this way). Variations in the software (e.g. storage or counting of states) have not been realized.

The tables reveal that we have actuator-dominated and sensor-dominated sub-problems. It is obvious that only the detection is involving sensors. If this sub-problem is analyzed isolated, a direct correlation between the quantities of sensors and solutions is established: One sensor performs exactly one idea.

Calculating q_1 and q_2 in the way described above for each sub-problem separately illustrates the lack of variation possibilities for ‘detecting’. Table 8 shows these performance calculations for each sub-problem separately. For calculation only sensors or actuators have been taken into account, depending on the S&A-domination of the sub-problem.

Table 8: Performances separated by sub-problem.

MEE	‘Transporting’ (actuator dominant)		‘Detection’ (sensor dominant)		‘Signaling’ (actuator dominant)	
	q_1	q_2	q_1	q_2	q_1	q_2
Festo MecLab	3.00	1.50	3.00	1.00	1.38	0.75
Fischertechnik RoboTX	2.83	2.17	1.25	0.50	2.00	1.00
Lego Mindstorms EV3	2.67	1.50	1.09	0.27	2.50	1.33
SD	2.83	1.72	1.78	0.59	1.96	1.03

Comparing these separated figures is showing additionally that Lego Mindstorms cannot compete with the other MEEs, due to the fact that in any sub-problem the q2-performance is less than 1. RoboTX has a relatively good q2-performance though it contains as low amount of actuators than Mindstorms does.

Compiling these figures to the categories ‘sensor-dominated’ and ‘actuator-dominated’ problems and calculating the averages allows us to make general conclusions about all three MEEs. This has been done in Table 9.

Table 9: Performances q_1 and q_2 according to domination.

MEE	Actuator dominated ideas		Sensor dominated ideas	
	q_1	q_2	q_1	q_2
Festo MecLab	4.38	2.25	3.00	1.00
Fischertechnik RoboTX	4.83	3.17	1.25	0.50
Lego Mindstorms EV3	5.17	2.83	1.09	0.27
SD	4.79	2.75	1.78	0.59

The q_1-performance (based on all found solutions) is significantly higher than q2-performance (based on different solutions exclusively). For instance, Mindstorms provides four times more total ideas than different ideas in case of sensor dominated problems. For actuator dominated problems this difference has even an average factor of 1.73. That means that for rating the MEEs according to their performance to support creative problem solving it is essential to know on which understanding of creativity according to the novelty of the products one takes base.

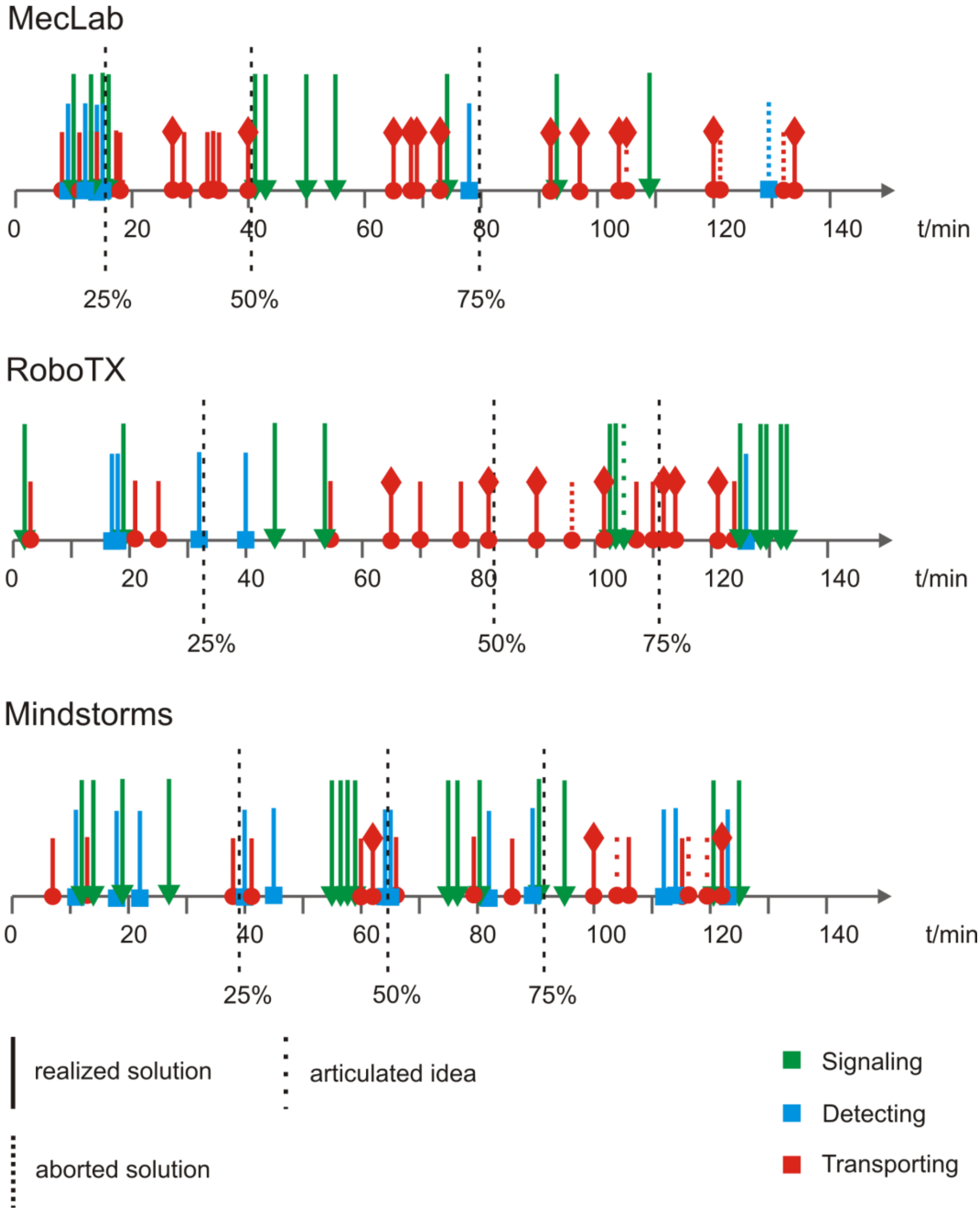

Figure 2: Timelines: solutions regard to learning media systems

The following visualization (figure 2) displays the finished solutions, aborted solution approaches and articulated solution ideas in depending on the time they occurred during the trial in one timeline per MEE. A different color and length of the marks is supposed to help separating the solutions for the three sub-problems (signaling, detecting, transporting). Additionally we added percentage-lines within the timelines to indicate the point when 25%, 50% and 75% of the total solutions have been found or articulated.

The percentage-lines indicate how fast the pupils can realize solutions with the MEEs. It takes more than half of the available time to come to 50% of the solutions (83 min) with RoboTX. Compared to MecLab (40 min), this is quite slow. In contrast, MecLab delivers many solutions within the first 20 minutes while the solution density gets lower as time passes.

Most groups have built combinations of the principles listed in tables 5, 6 and 7. Such combinations have been counted as a novel solution. Combinations just came up in the sub-problem ‘transportation’ and are highlighted with a rhombus in figure 2. All occurred combinations connect at least one actuator with at least one mechanical component (e.g. gripper arm places ball + ramp accelerates ball). Table 10 displays the quantity of solution combinations per MEE and the amount of different solution combinations. Repetitions occurred quite seldom, as the percentage of novelty in the meaning of ‘big C’ (solutions have to be novel for all participants, not just for the single group) shows.

Table 10: Percentages of different solutions.

MEE	Total solution combinations	Different solution combinations	Percentage of novelty (‘big C’)
Festo MecLab	12	10	83%
Fischertechnik RoboTX	6	4	67%
Lego Mindstorms EV3	3	3	100%
Overall	21	17	81%

Combining different solution principles to get more countable solutions has been used by the participants due to the lack of non-combinational solutions (the participant groups tried to compete against each other; the group with the most solutions would be the winner). We plotted timelines of each group, which showed that non-combinational solutions mostly have been the first choice, while combinations of different solution principles were developed later. Displaying these timelines would go beyond the scope of this article though. Considering this, Mindstorms is the most flexible MEE because it doesn’t force the user to use combinations to raise the quantity of solutions. MecLab on the other hand could not compete at all if combinations of different solution principles had not been rated as novel solution.

Conclusions

Due to this being a pilot study based on a novel research design, a short review of the studies’ design has to be done. The study delivered lots of data that can be a basis for many different kinds of analysis. In the paper at hand we made use of just some of the captured data. We conclude that the study delivers a sufficient data to find answers to the research questions and confirm or discard the hypothesis of this pilot. Because the times of the completion of solutions and the created products have been recorded, the study design is able to deliver data as a basis for more detailed analysis. For instance it would be possible to draw conclusions by analyzing the sequence of solutions, the time it took to create them, the further use of developed ideas and much more for the MEEs or for groups separately. We did not focus on the creating process but on the products (Glaveanu, 2011). For a research design more orientated on a single person the current design can be extended by a monitoring of the actions of the single pupils. An extension would also be necessary to analyze the software side of the solutions more in detail.

Our leading question was to find out, if MEEs with different components affect the creative problem solving of pupils. To clarify this, we formulated more specific questions and three hypotheses which we have evaluated with the described study. It has to be kept in mind that our data has been recorded within a pilot and therefore is not sufficient enough to make reliable conclusions. But we are confident enough to formulate some finding in the meaning of tendencies.

Focusing on the figures in table 3 we must consider, that it is difficult to come to general conclusion about the relation between the quantity of sensors and actuators and found solutions. The quotient q1 (which we call ‘performance’) varies very much and indicates that the pure quantity of sensors and actuators is not relevant for the amount of solutions. Hypotheses 1 (H1) has to be discarded as far as we refer to the quantity of solutions this way. So far we must consider, that it seems simply not possible to adapt the findings of Davies et al. who provided the evidence that the range of resources benefits creativity (Davies et al. 2013). This finding does not significantly change if we turn the understanding of creativity from his ‘little C’ approach to a ‘more big C’ approach (Plucker & Beghetto, 2004). Table 4 is exclusively taking solutions into account that are novel for the whole group of participants (Amabile, 1996) at the moment they occurred. The calculated quotient q_2 (‘differentiating performance’) is a better descriptor for the MEEs, because it does not implicitly integrate repetitions done by users and indicates more what the MEE enables the whole group to do. The q_2-quotients also vary a lot; Mindstorms could not take an advantage of the bigger amount of sensors and actuators. All three MEEs provided nearly the same amount of novel solutions; the amount of sensors and actuators was irrelevant. Once more we must consider that we cannot confirm the described results of Davies et al. (2013) and we have to discard hypothesis 1 (H1).

Tables 5, 6 and 7 list all found solutions separated by MEE and by sub-problem. Regarding these tables, a resemblance is striking. For detection of the ball any system performs one solution per sensor at most. The same finding can be concluded for signaling a goal. Table 8 shows the performances q_1 and q_2 according to the three sub-problems and confirms quite poor performance for detection and signaling. Q_2 even shows that not any available sensor has been used for detection ($q_2 <= 1$). This can be explained by the flexibility of the available sensors: Sensors are quite specific components that have been designed for a specific use. A light barrier for instance, which has been part of MecLab and RoboTX, can just detect the presence of an object. Though the color sensor of Mindstorms is multi-functional, it cannot be used in multiple ways, because the object to be detected is determined by the problem setting (a ball that has to be detected within the goal). The optical sensors of all three MEEs could detect a large variety of objects not just balls, but nevertheless the task minimizes the flexibility of the sensor. That means that the operator space is quite small (Edelmann & Wittmann, 2012).

It could be assumed that sensor-dominated problems in general inhibit creativity due to the specific use of sensors at all. Table 9 shows that the q_2-performance of all three MEEs is significantly higher for actuator-dominated solutions than for sensor-dominated ones. In average, a sensor-dominated context performs 4.7 times worse than actuator-dominated context. We justify this with the described less variability of the sub-problem ‘detecting’, which seems to be relevant for the creative problem solving process. The results for the actuator dominated sub-problem ‘signaling’ displayed in table 8 are also remarkable. Even though this sub-problem does not have the same restrictions like ‘detecting’ caused by a lack of variability of the task, it also has poor q_2-performances compared to ‘transporting’. We think that signaling like detecting is a determined process that can directly and easily be done with specific components. For instance LEDs like other optical actuators cannot do many different things but indicating information. This brings us to the conclusion that the relation between the given problem and the available components could be an important factor for the creative problem solving process: If there are components available that directly support the demanded function, the creative process is hampered. Whenever a desired function can be realized too easy, there is no need to be creative any more. The problems’ barrier to get to the wanted state is not strong enough; the problem becomes a task-like character because the solution way is obvious (Gerring, Zimbardo, 2008). Not any component is generally a barrier for creativity which leads to a low creative use of available components. But any component may become an inhibition if there is a direct feasibility between the problem and the components. This conclusion is nurtured by the performances for ‘transporting’, which are the highest compared to the other two sub-problems (table 8). There is no specific component included in any of the used MEEs that is explicitly made for transporting things or shooting balls. Due to that, one must be creative to find a solution. Considering that, we also have to discard hypothesis 2 (H2). Although we can confirm the assumption that physical objects and material resources do have a relevant influence in creativity (Galewska-Kustra, 2016; Gralewski, 2016). For generating a conclusion about the effect of the specialization of components, the context always has to be taken into account.

For the evaluation of hypothesis 3 (H3) an analysis of the timelines in figure 2 is necessary. Comparing the realized solutions at the beginning of the trials explicitly shows an advantage of MecLab. Within less than 20 Minutes each participant found a solution for all three sub-problems of the given problem and created a working machine. After 20 Minutes more, already 50% of all solutions have been realized just by varying the 'transportation'. When 50% of all solutions have been realized, the upcoming of solution combinations rises. RoboTX needs a much longer (80 Minutes) to come to 50% of the solutions. It is interesting that similar to MecLab much more combinations of solutions are used after that point. This effect could be observed for the Mindstorms groups too, although there are just three solution combinations. As already mentioned all solutions combinations included at least one mechanical component. These mechanical components had to be constructed on the base of many single mechanical parts (for instance ramps have been used quite often in combinations). These single parts (bricks, rods, struts, plates and so on) have an abstract character. There is no specific use for them, they are universal. They are comparable to the color an artist of painting is using for being creative. The color could be used for drawing anything; no specific motive can be derived from the paint. In contrast more complex components like a motor or a cylinder implies typical uses. This is where the disciplinary context becomes important: Because these components are used in technical problem solving context, a technical application may be attributed to the component. This means that the use of context-attributed components is preferred generally. This can be seen as a justification for the fact that universal components that are not directly attributed to technology and the context the creative process takes part in, are regarded with less priority compared to technology-attributed components. We see this as a confirmation for the domain-specific character of creativity. Due to this finding hypothesis 3 (H3) can be confirmed. With this insight we agree with many authors who emphasize the relevance of the domain the creativity takes place in (Baumert, 1996; Runco & Pritzker, 1999; Plucker, 2000; Baer, 2016).

According to our leading research question we found, that the context, in which a creative problem solution takes place, plays a dominant role for the rating of the properties and the character of a MEE. One the one hand, the global technology context animates problem solvers to prefer components and ideas that match the disciplinary context better (sensors, actuators) than universal components that are not attributed to technology directly. Though there are preferred and less preferred components, the creativity is not affected in a way that a lack of technology attributed components (like sensors and actuators in mechatronic contexts) inherits the creative outcome as long as a MEE provides alternative components that may be used for create unconventional solutions. Depending on the intention one has, a lack of specific components may even lead to 'a higher quality' of creativity in the meaning that more unique solutions may be created. The specific problem even sets up a more specific context and is of dominant relevance, too. Finding solutions with components that directly match the needed functions is relatively easy. In this case, the need to be creative is low what means an inhibition for creativity. Creativity can be supported if there are needs that cannot be fulfilled by the trivial use of a given component. Based on the results of our study we disagree with the findings of seven studies that researched the making of products. These studies came to the conclusion that resources have to be appropriate to stimulate creativity (Davies, et al. 2013). Our study concludes that resources may not be too appropriate to enhance creativity. It is possible though that this is a specific effect of the domain of technology.

We think that there is a domain-creativity-paradox in the context of technology: On the one hand technology can be characterized as the realization of a wanted state and always aims at the optimal solution with the use of minimal resources. On the other hand creativity needs options and variability for unconventional and non-optimal solutions. For working creatively in technology classes, one must find the right balance.

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