The Relevance of Trial-And-Error

Can Trial-and-Error Be a Sufficient Learning Method in Technical Problem-solving-contexts?

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The popular problem-solving method 'trial-and-error' could be regarded as a low-threshold method that does not support cognitive activity. This opinion can be even emphasized by observing persons who try to find a satisfying solution by trialing with physical objects, because they may look as if they do not think at all. Regarding the trial-and-error-method in more detail, this opinion seems to be deficient. In fact, there are different variations of trial-and-error. Most of them require intensive thinking processes and focus on learning about the problem and its solution options. A pilot study revealed findings and showed that trial-and-error activities initialize important learning processes. It often occurs in several loops, especially if the problem solver is an unexperienced novice in a trial-supporting space. Students of a research-oriented course engaged 15 participants of different experience levels with an obstacle, that should be bridged over with not more than 10 sheets of paper. The analysis of the trials showed, that novices found as capable solutions as more experienced persons did. While they needed more trials, they all developed the essential idea of folding bending-resistant profiles of paper. These results prove that persons are learning while trialing.

Keywords: technology education, problem solving, problem representation, trial-and-error, space

Theoretical approach

A problem can be described as a gap between two states: A given one and a wanted one. The wanted state cannot be achieved directly by applying a strategy that guarantees a successful solution in this specific situation. There is an obstacle between the two states that turns the situation from a simple task to a more or less complex problem (Edelmann & Wittmann, 2012). The problem-solving-process is described in literature as a stepwise process (Funke, 2003). The quantity and the description of the steps vary. Some models claim that problem solving is not proceeding in linear steps. Persons tend to switch between the steps very flexibly; steps can be skipped or repeated any time (Huettner, 2005). Thus, some models describe the problem-solving process as a cycle of seven steps (Hayes, 1989; Bransford & Stein, 1993; Sternberg & Williams, 2010). However, at the end of problem-solving is an evaluation step for checking if the solution matches the needs of the problem appropriately. This is a similar pattern like Test-Operate-Test-Exit (TOTE), which is a well-known principle in psychology (Miller, Galanter & Pribram 1960).

There are also many different methods to explain how solutions are to be found by persons (Wenke, Frensch & Funke, 2005). Authors differentiate problem solving in many various methods like means-ends analysis, forward or backward working, generate and test, operator subgoaling, subgoal decomposition, difference reduction, restructuring, strategy applying, creativity or system thinking (Newell & Simon, 1972; Sternberg & Williams, 2010; Edelmann & Wittmann, 2012). Anyhow, there is one method that is referenced by nearly all authors: There does not to be a question that the trial-and-error-method (T&E) is an established problem-solving-method. T&E does not declare how a solution idea came up, but it describes an activity pattern for evaluating solution ideas. It provides explanations for the decision of following up or discarding a solution idea. If the evaluation result is negative, a different idea has to be generated and has to be evaluated again. This way, another T&E-loop will run through. Once the evaluation delivers a satisfying result finally, the current problem is solved.

The quantity of trials depends on the complexity of the problem, the limitations given by the space and the experience level of the problem solver:

- Assuming that people tend to divide complex problems into several sub-problems that are less complex and easier to handle (Huettner & Toennsen, 2019), one can consider that complex problems will probably be solved by passing multiple T&E-loops (Doerner, 1976; 1983). Dividing complex Problems in sub-problems and solving them stepwise is a common way to realize extensive projects in the domain of technology (Mueller, 1990; Conrad, 1998).
- As spatial theory claims, the space where action is going on should not just be seen as a geometrical room or as a place located on a geographically defined spot (Loew & Geier, 2014). Interaction turns a mindless 'container' of physical objects to a social relevant space. The spatial theory points out that any action of persons with objects in a space is an interaction and that any object is giving relevant feedback. Thus, physical objects can be as an important interaction partner as other people (Loew 2001). The more physical objects are part of the problem situation in a space, the more options for interaction and problem-solving can be provided.
- Persons with a lack of experience, knowledge or competencies in a problem context, are novices in the specific problem context. There is a high chance that they will potentially execute more trials than experienced persons. T&E even can be (the only) sufficient method in a problem situation (ultima ratio) if a person is not aware of any solving options at all (Doerner 1985). Huettner (2005) points out that T&E also is an established pattern in technology education contexts. In problem-oriented learning scenarios students activate their knowledge and competencies and develop them further by solving didactical indented problems.

T&E can be easily underestimated by assuming that any trial is just a tryout of solution ideas that occur randomly while 'playing' around (Kipmann 2020). Wiesenfarth (2019) states that T&E is just trying without any concept. However, Edelmann & Wittmann (2012) postulate that often strategies are applied for generating solutions that can be evaluated by trialing. They claim that aimless T&E (trialing without a solution idea) is an exception. Furthermore, even the evaluation process is not necessarily simple but can be a complex process too. Hypotheses and evaluation criteria must be developed and test results must be analyzed. Even modifications based on test results can require challenging thinking processes.

Regarding the aim of T&E more in detail, we can differentiate two different motivation types:

1. Exploration: A person is exploring a problem space by modifying variable aspects of the problem setting and watch the consequences. The aim of T&E of this type is to explore the problem space and to check out effects of possible options. When a person gets some knowledge and experience in a problem space, she / he gets aware of possible options and how they could take effect in the problem. This way, a person will learn about the problem and its transformation options. Both are required for finding a solution.
2. Finalization: A person is trying to find a final solution for the entire problem. Even if someone concentrates on just a detail, the intention is to solve the problem at all. A found solution can also be optimized if there is a motivation to find a better solution. Anyway, this type of T&E-action aims on realizing a satisfying solution.

Based on this theoretical reflection, I postulate four hypotheses:

1. Due to a lack of experience, knowledge and competencies novices are executing more T&E-loops than experts do and it takes them a longer time to find a satisfying solution.
2. Because novices need to gain experiences about the problem scenario and the problem space before they can finally solve the problem, they are supposed to do more exploring T&E than experts with relevant experiences.
3. After experiences have been made, finalizing T&E can be supposed to be done. By optimizing solutions persons are getting more and more experienced in the problem context and the solutions are becoming better.
4. If the problem does not need specific education and if advanced solutions can be found on the basis of general knowledge and competencies, novices and experts can be expected to find solutions of the same performance level.

The study

Verifying these hypotheses has been the issue of a pilot study that will be described in the following section.

Introduction

Newell & Simon (1972) claimed that a problem is represented in a problem solvers mind. This internal problem representation contains the current and the target stages as well as transformation options. Before a transformation will be executed, the probability of success is estimated by the person. For doing that, the person applies a transformation imaginarily on the internal problem representation. An internal trial is executed in mind. The generation of the solution idea as well as the internal trial are demanding thinking processes. Making conclusions about the solving process and how it is going on is difficult, because thinking processes cannot be observed and captured directly (Ericson, 2003). Even using methods like 'thinking aloud' (Watson, 1920) cannot represent the real thinking process but just a verbalization of it.

But how can problem-solving be assessed? Creativity assessments can be considered for this purpose, because creativity and problem solving are related; some even consider creativity is just a variation of problem solving (Seiffge-Krenke, 1974; Lubart & Mouchiroud, 2003; Edelmann & Wittmann, 2012). Urban (2004) claims that problems are the only reason why someone is creative. It can be subsumed that problem solving is inextricably woven with creativity (Dishke Hondzel & Gulliksen, 2015). Assessments like the 'Torrance Checklist of Creative Positives' (Torrance, 1973) or the 'Creativity Checklist' (Johnson, 1979) aim on the process of working creatively. Others focus on the outcoming product of creative working. For instance, the 'Creative Product Analysis Matrix' and the 'Student Product Assessment Form' provide criteria-oriented rating systems to analyze creative products (Besemer & O'Quin, 1987; Reis & Renzulli, 1991).

But none of them take the domain specific feature of external problem representation into account: If the external space provides an environment that can be transformed as easy and quick as in imagination, the internal solution directly can be applied in material reality. Actions like trials with objects of the external problem representation in the surrounding space can be recorded or documented by observers easily and may provide valuable information about the solution process. But the relevance of objects for problem solving can be assumed to be very different:

- Peripheral objects support the solution process by providing a basic infrastructure. They do not have specific functions for the solution process but rather basic functions. These objects might be exchanged by similar objects that can provide the same functionality without any relevant impact on the solution process. For instance, a table, a chair or a pen are non-specific peripheral objects.
- Processing objects are necessary tools for the transformation of a problem state. They never become a part of the product itself, but they have direct influences to the solution process. Due to their properties, these objects can enable or hamper a person's processing opportunities. Machines and tools are typical processing objects. For instance, specific types of saws may be used for cutting wood but not metal or making straight but not curved cuttings. This characteristic will have an impact on a person's solution options.
- Product forming objects have the potential to get a material part of the solution product. These objects affect the solution process and the product essentially. Like processing objects, they may open or inhibit solution options. Some product forming objects just allow specific options; others may be very flexible and may serve various options. As these objects constitute the final solution product, their final use is 'frozen' in the product and can be analyzed even when the solution process has passed.

In the domain of technology, processing and product forming objects like tools, machines, materials and components are important. Research of problem-solving in this domain has to include processing and product forming objects. Spaces like workshops or fabrication laboratories provide specific objects and specific processing options. Spaces are extremely relevant for problem solving when the problem is determined by processing and product forming objects, because they may provide a 'hidden curriculum' and may evoke specific interactions (Goehlich, 2011) depending on the options they support.

Methods

This pilot study has been implemented by students and has been part of one of my research-oriented university courses. Unfortunately, we had to deal with strong restrictions due to corona pandemic. We were neither able to get together with participants nor to use spaces like workshops. To answer our research questions anyway, we developed a setup that enables the students to do the assessment at home. Therefore, we had to find a problem that can be solved with product forming objects of any household and without technology specific processing objects. To avoid new contacts, household members had to participate as test subjects. That means that we could assume a randomly spread level of experience. According to the three implications that affect the quantity of T&E-loops as described in theory section, the complexity of the problem and the limitations given by the space should be the same for all participants. We decided to engage them with two stacks of books (or something similar) positioned at distance of 25 cm to each other. The problem was to bridge this gap with just 10 sheets of paper and some glue. These product forming objects are easily available and can be fold or teared without any tools. The only processing objects that could be used have been six clothespins to fix the paper while gluing it. The bridge should be as stabile as possible. The performance of the solution has been assessed by straining the bridge with objects of defined weight. If persons wanted to build another bridge or try out further ideas (optimization) they got additional paper. Anyway, a solution should consist of not more the ten sheets. The participants could perform as many T&E-loops as necessary to come to a satisfying solution. We neither limited the quantity of loops and time nor we set a minimum weight the bridge should carry.

We observed the solving of this problem of 15 participants (n = 15). We asked if the person is self-assessing to have a low or a high experience level in building bridges with paper. After introducing the problem, the solving work started. We separated the problem-solving activity in T&E-loops and documented the following data:

- Question 1: When a new T&E-loop has been started and the participant began to process the paper, we noticed the time and ask the person for a plan.
- Question 2: We asked if the person is up to explore or finalize the problem.
- When an observable solution idea was canceled or tested we also noticed the time and asked what findings have been acquired in the T&E-loop (Question 3). We also asked, if the person expects this finding to be unimportant or important (Question 4).
- When a solution was evaluated in the external problem representation we took a photo and documented the weight that the bridge has been strained with.

On the basis of this data we were able to calculate the duration of thinking activity (internal problem representation) and the duration of thinking and working on the external problem representation. We also could sum up the amounts of exploration and finalizing aims as well as the quantities of important and unimportant findings. Averages and standard deviations of these values could be calculated.

In addition to this quantitative analysis the answers of questions 1 and 3 could be analyzed more qualitatively. Even the photos were taken into account. We used the qualitative analysis to find out if and when the persons developed the key idea for stable paper-bridges (folding profiles).

All involved persons participated voluntary and of course have not been harmed during this study. They decided how much time and engagement they wanted to invest and never any performance pressure has been put on the persons. We just collected the necessary data for our specific research interest and documented no personal information like sex or names. Token photos do not show faces or persons in a way that makes them identifiable.

Results and discussion

While the assessment has been made together with students, this report is written by myself only. I report of a pilot with n = 15 here, so the significance of the results of course is low. Higher significance requires more participants. Another limitation is the specific problem we developed. Though it focusses on product forming objects, it is not reflecting an entire specific domain like technology. Anyhow, some preliminary conclusions should be made to show what type of results this research design can provide.

The following table displays some average data divided into unexperienced and experienced participants.

Table 1. Average times and T&E-loops of novices and experts (times in minutes)

Average values	Novices (n = 10)	Experts (n = 5)	Both (n = 15)
Time per T&E-loop	06:25	07:42	06:51
Thinking operations	00:57	01:36	01:10
Thinking and practical operations	05:28	06:05	05:40
Amount of T&E-loops	6.2	2.4	4.9
Total working time	32:35	17:40	27:36

The table shows clearly that it takes novices nearly twice the time to come to a final solution. They also need more than twice as much T&E-loops as the experts. Even though these findings seem to be quite trivial, they confirm hypothesis 1. This supports Funke (2003), who describes problem solving as a process of several steps and Huettner & Toennsen (2019), who believe that complex problems will be divided into sub-problems. The assumption that complex problems result in multiple T&E-loops can be confirmed by these data also.

Furthermore, the table reveals additional information: It should be noticed that the experts invest more time to pass a T&E-loop than the novices do. The experts invest nearly 50% more time in thinking operations. In accordance to the theoretical approach this indicates that there is more knowledge that has to be considered in mind before transformations will be done to the problem physically. Evaluating them in the internal problem representation takes some time. In general, we can conclude that experienced problem solvers are faster, take less trials with physical objects and spend more time with thinking activity than unexperienced problem solvers. The concept of an internal and an external problem representation (Wiesenfarth, 2019; Binder, 2020) matches to these findings: Experienced persons can apply more thinking-only-phases just because they build up an internal representation in mind.

Another interesting finding is that all participants prefer working on the problem in the external problem representation. They spend about 80% of time on trialing with physical objects while just investing 20% for pure mental thinking. There is just a very little difference of 1% between experts and novices. The introduced concept of different types of physical objects meets these findings. You can't postulate general findings with n = 15, but the difference in this study is remarkably high. If this design ever will be repeated with more participants for reliable results, this could be a finding with a relevant impact on (problem based) learning in many disciplines that include physical objects in their problem spaces.

This table displays how the motivation types of all practiced T&E-loops is distributed between novices and experts.

Table 2. Percentage distribution of T&E-loops according to the motivation type

T&E motivation type	Novices (n = 10)	Experts (n = 5)	Both (n = 15)
exploring	48%	17%	37%
finalizing	52%	83%	63%

Nearly half of all T&E-loops of the novices aim on the exploration of the problem space while just one fifth of the expert's T&E-loops serve the exploration. Thus, hypothesis 2 also can be confirmed. The lack of experience requires learning about the problem space. If problem solvers are aware of this lack, they decide for exploring-type T&E consciously. The data prove that the novices have learned a lot about stability of paper-based materials. Because of this, even 'just trying' is no T&E without strategy or ideas. The activity is very open and the aim is undefined. Only this way orientation can be achieved when a person does not have any approaches for trialing with defined aims. Due to this, I disagree with Kipman (2020), who does not see any benefit in aimless trialing. The benefit is given just because no fixed goal is aimed at. Trialing very open minded does not mean that there is no concept and no benefit behind trialing without a specific solution idea.

A key for building a stable paper bridge is to roll or fold some sheets to get profiles that are much more stable than flat paper can be. Table 3 displays how long it took the participants to develop this idea:

Table 3. Acquisition of the key idea of folding or rolling profiles (times in minutes)

First profile building	Novices (n = 10)	Experts (n = 5)	Both (n = 15)
In T&E-loop no.	3.1	1.0	2.4
Time after starting the work	09:09	00:21	06:13

The novices build the first profile consciously in the third trial (average 3.1; 9 minutes after starting the work) while the experts used profiles right after the beginning. This is remarkable, because no additional information has been given to the novices. They came up with this idea just by performing T&E and gaining experiences. The T&E-method seems to be a sufficient learning method. Further studies could put a focus on the question if this a general phenomenon or if it is limited to problems similar to this. It can be assumed that the physical problem space is an important factor as mentioned in theory section before.

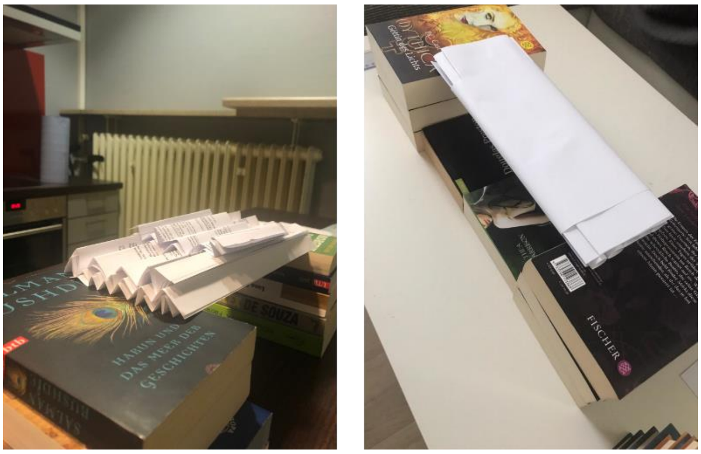

Figure 1. Bridges with maximum carrying capability (left: 3337g by expert, right: 4500g by novice

A deeper regard on the assessment protocols revealed that all experts performed the first trial with the motivation of finalizing the problem. This may be an indicator that more experienced persons tend to dare to solve the problem off the cuff. And they have good chances to do so, because all of them used profiles right from the beginning.

The performance of the solution could be evaluated easily by straining the bridges with objects of known weight. Regarding the growth of the performance, another indicator for successful learning while doing T&E becomes visible: While the experts could rise the performance by a factor of 1.8, the novices were able to increase the performance by a significant growth factor of 32.8. Even some novices started the first T&E-loop with the key idea of folding profiles. Those, who did not start this way even performed a growth rate of 62.1. These figures indicate that the experts have learned relevant aspects for paper bridge building before the study and they remember. The novices learned these aspects in the study by collecting and analyzing the experiences they made. The growths of the solution performance (of the novices) are displayed in this diagram:

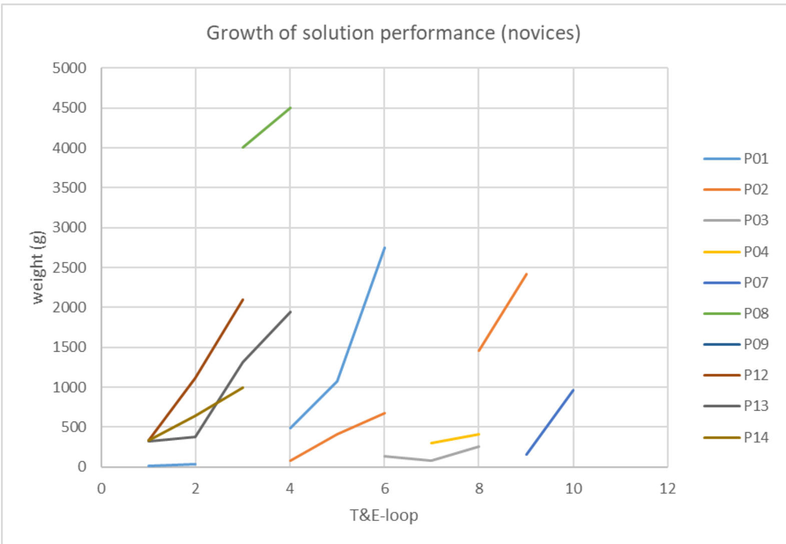

Figure 2. Trends of the carrying capacities of the novices by T&E-loop

The data lines have gaps if a person canceled an idea and started a new T&E-loop without testing the performance. Even though it must be considered that the x-axis is not a timeline and we already described that exclusive thinking takes a relatively short duration, the diagram shows that thinking in mind and trialing in physical space often alternate. This supports the concept of problem solving as a non-linear, cyclical process. Switching between solution steps is possible and may be used very flexible (Hayes, 1989; Bransford & Stein, 1993; Huettner, 2005; Sternberg & Williams, 2010). Anyway, the strong increase of performance is visible and hypothesis 3 can be verified on this basis.

Furthermore, the diagram shows differences between the participants. This characteristic is emphasized by the high standard deviation of the growth factor of SD = 57. Many persons could even multiply the performance. But there also is a group that was not able to achieve as high performances as others did (< 1000g). It is striking that the 'low performers' did many T&E-loops, but they also cancelled a lot of ideas without testing them. This is an indicator that amplifies the importance of practical evaluation in the external problem space. As declared in the theory section, an internal representation in mind is just a copy of the real problem. If it is incomplete or incorrect, trialing on the internal reproduction can lead to deficient solutions. By not trialing in reality persons may get a lack of synchronization between the external and the internal representation (reality and mind).

The following table shows some solution performance data more in detail:

Table 4. Carrying capacities and standard deviations

Average values	**Novices (n = 10)**	**Experts (n = 5)**	**Both (n = 15)**
Carrying capacity at 1st trial (g)	684	1021	796
SD	1245	574	1057
Maximum carrying capacity (g)	1863	1725	1817
SD	1182	992	1088

As expected the novices started with 40% lower capacities as the experts did. This difference could be expected to be higher, because the experts already knew the key idea of profiles. It must be considered that even some novices began constructing profiles right away. Those who did not start with profiles performed a capacity at their first trial of just 70g with a standard deviation of 67g. This emphasizes the importance of profiles for the problem solution. In fact, the idea of building profiles can be seen as the 'hidden curriculum' of the problem setting (Goehlich, 2011). The experts started with 1021g. The standard deviation of 574g is relatively low compared to the other values. This means that the key idea of using profiles is quite a safe and reliable solution idea.

Of special interest are the maximum carrying capacities. They show that even the novices can find as performant solutions as experts do; they even perform 8% better in the final solution. Obviously, they were able to learn by doing T&E an become as experienced as the experts. The standard deviations get closer to each other, too. This indicates that the novices have become experts. These conclusions confirm hypothesis 4: You can become an expert just by doing T&E.

Final conclusions

All four hypotheses could be confirmed. The participants have gained experiences and learned independently without any instructions how to make stabile paper bridges just by doing T&E. Unexperienced participants developed the key idea of creating profiles and produced solutions of the same performance level as experienced participants did. It takes them longer and more trials have been done, but this 'overhead' is where relevant learning happens. Due to that T&E can be considered to be a worthwhile learning method in didactical contexts and most of the theoretical findings this pilot study is based on as described in theory section can be confirmed.

This does not include trialing without a conscious idea: According to the results I conclude that the open-minded trialing is a specific and sufficient variation of T&E that supports persons to get experiences about the problem without any solution approach and enables them to develop further ideas that can be used as a basis for aim-based trialing. Due to this, I reject approaches that see T&E as an insufficient operation without any value for the solution (Wiesenfarth, 2019; Kipmann, 2020).

The results also support the concept of spatial theory (Loew & Geier, 2014) and emphasizes the relevance of physical objects in spaces: Those objects were the only available interaction partners in the setting. Nevertheless, all participants found out the key idea for a performant solution. The objects in the external problem space had become an information source. By trialing with them, the objects had become an interaction partner in this setting. Therefore, Loew's conclusion that objects can communicate with persons by interacting with them can be supported (Loew, 2001). As already mentioned before, an unhampered interaction with objects in T&E-settings require flexible objects and unlimited availability. Due to that, problem spaces will not be suitable for T&E when physical objects may be damaged, trials could be dangerous or materials are too valuable for several T&E-loops. As far as reversable learning systems like construction kits will be used, T&E can be applied without concerns.

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