Progress in Science Education
2020, Vol 3, No. 1, 9-25
ISSN 2405-6057
DOI.10.25321/prise.2020.960

HOW SHOULD STEPPED SUPPORTING TOOLS BE DESIGNED TO SUPPORT NON-MAJOR CHEMISTRY STUDENTS WHILE SOLVING TASKS IN ORGANIC CHEMISTRY – RESULTS OF A THINK-ALOUD STUDY

Jolanda Hermanns[1]

[1]Zentrum für Lehrerbildung und Bildungsforschung und Institut für Chemie der Universität Potsdam
*Please adress all correspondence to Jolanda Hermanns, e-mail: jhermanns@uni-potsdam.de (ORCID: 0000-0001-7422-6350)

ABSTRACT
In this article the use of stepped supporting tools by non-major chemistry students will be discussed. The students used this scaffold while solving a task on the electrophilic addition on the double bond. To know how the students proceed a think-aloud study with ten students was conducted and will be discussed here. The results show that the students are then successful in solving the task if they have sufficient prior knowledge and methodical skills. When they lack these knowledge or methodical skills the stepped supporting tools can only partly support the students.

Background: Scaffolding for supporting students while learning chemistry is described in the literature (Taber, 2002; Livengood, 2012; Hermanns, 2019). For non-major chemistry students stepped supporting tools were developed. The use of these tools were investigated in a think-aloud study.

Purpose: The results of the think-aloud study should be used for the future design of stepped supporting tools or another scaffold.

Sample/Setting: Ten non-major chemistry students who study life sciences or nutritional science participated in the think-aloud study on the use of stepped supporting tools.

Design Methods: A qualitative (think-aloud study) method was used.

Results: The stepped supporting tools are helpful when sufficient prior knowledge and methodical skills were available.

Conclusions/Implications for classroom practice and future research: The new design of the scaffolds should provide the required prior knowledge that is needed as well as methodological strategies for the task at hand.

Keywords*: non-major chemistry students, organic chemistry, self-regulated learning, scaffolding.*

Received*: January 2020. Accepted: April 2020*

© The authors, 2020
Published by CERN under the Creative Common Attribution 4.0 Licence (CC BY NC SA 4.0)

1 INTRODUCTION

"Organic chemistry is a rich, vibrant discipline and gives its central importance to science, it is imperative that students develop a sound, conceptual understanding of the subject" (Grove & Bretz, 2012). The field of organic chemistry therefore consists of numerous compounds, reactions and their mechanisms. Though being so, many students try to rote memorize all contents instead of building conceptual knowledge and are not very successful in doing so (Cooper & Stowe, 2018). Several concepts to build up conceptual knowledge are published (Cooper et al. 2013; Flynn & Ogilvie, 2015). Conceptual knowledge in organic chemistry is in our course also the main goal, although we observe that our students struggle with building up those knowledge. To support students in their learning process, we developed stepped supporting tools as a scaffold when solving problems in organic chemistry. Although stepped supporting tools are evaluated as helpful by the students (Hermanns & Schmidt, 2019), little is known about the processes that occur when the students use the tools while solving tasks in organic chemistry. A think-aloud study on the use of these tools was therefore conducted and evaluated.

2 RESEARCH BACKGROUND

Before formulating the research goals and the study in detail a review on all relevant research results in the different fields that are used as the theoretical basis for this study is given below.

2.1 Scaffolding

For chemistry teaching at universities, different examples of scaffolding are found. Taber (2002) describes scaffolding as the possibility to activate students. The scaffolding supports the students appropriately. Examples are DARTS (Directed Activities Related to Text), POLES (Provided Outlines Lending Support) and PLANK (Platforms for New Knowledge). One possible DARTs type is the use of passages where words are missing. The learner then has to read the material to work out what the missing words are. When PLANKs are used as scaffolds, ideas are presented that are already available to the students, but they are now arranged in a form which supports the students to reorganize their knowledge and so build up new knowledge. The scaffolds POLEs are provided by the teacher. The support is given while the learner develops understanding and confidence in a new topic. Hilton, Nicols & Gitsaki (2019) use digital media as scaffolds in practical courses in the laboratory. Specific tips given to support students while working on their homework is also a form of scaffolding (Livengood Lewallen, Leatherman & Maxwell, 2012). An interview study on the problem solving of students as basis for future use in the development of stepped supporting tools (SST) for chemistry education is described by Fach, de Boer and Parchmann (2007). The first application of stepped supporting tools in chemistry education at university is described by Hermanns et al. (2019). This method is known from using at school (Hänze, Schmidt-Weigand & Stäudel, 2010). Stepped supporting tools can be used in partner and group work (Hänze et al., 2010 and Leisen, 2003), but also in individual work (Hermanns et al. 2019). Hänze et al. (2010) describe stepped supporting tools as "suitable to support the independent learning of pupils while working on tasks and problems. Tasks using stepped supporting tools can improve specialist learning". An individual person using stepped support decides independently which tools to use. The stepped supporting tools prevent failure while completing the task, because they show the correct solutions for every single step.

In order to adjust the stepped supporting tools to the needs of the students and to access whether the tool is suitable for the task at hand, one task on the electrophilic addition on alkenes was examined in more detail in this think-aloud study.

2.2 Electrophilic addition as an example in science education research

In a traditional course on organic chemistry the mechanism on the electrophilic addition on the double bond is usually the first mechanism using the concept of electrophiles and nucleophiles. In the new curriculum of Flynn and Ogilvie (2015) the mechanism on the electrophilic addition is discussed after acid-base reactions and reactions with nucleophiles without leaving group. The addition of bromine to cyclohexene was used in an interview study as a warm-up problem so that the participants could get used to the interview process (Bhattacharayya & Bodner, 2005). Grove and Cooper (2012a) and Grove, Cooper and Rush (2012b) used the electrophilic addition as an example in their study.

For this study the electrophilic addition on the double bond was chosen, because in our curriculum it is the first mechanism (after the radical substitution reaction of alkanes) discussed in the lecture.

2.3 Think-aloud studies

The think-aloud method provides insights into the mental processes of test persons. In voicing their thoughts out loud during an activity, conclusions regarding their impressions, feelings and intentions can be drawn. Originally, the method was used in software development to test usability. This method incorporates the target group with their specific needs into the development process. (Fromman, 2019). Because the think-aloud method provides detailed information on the thought process, the method is also used in education research. Insights can be gained into the problems students have while solving a task. With the think-aloud method, the student is asked to think aloud (Van Someren, Barnard & Sandberg, 1994). Ericsson and Simon (1993) state that thinking aloud does not disturb the problem-solving process, because the test persons are focused on solving the task. The think-aloud protocol can be incomplete, however, if the test person does not verbalize all thoughts.

Think-aloud studies are used in the natural sciences when investigating how students proceed while solving tasks. Chi, Bassok, Lewis, Reimann and Glaser (1989) report on a think-aloud study on solving tasks on the topic of mechanics. Jeon, Huffman and Noh (2005) report on a think-aloud study on problem-solving in chemistry involving partner work.

Bowen (1994) uses a manual for interviewing students while they solve tasks in chemistry. The questions therefore intervene in the thinking process. Van Someren, Barnard and Sandberg (1994) point out that the only intervention should occur when the test person stops speaking. Needless interventions and assistance should be avoided. In the think-aloud study that is discussed in this paper, therefore, the students should only interact with the materials (task and stepped supporting tools)

3 METHODS AND DATA

3.1 Research goals

This study was conducted to gain insights in the problem-solving process of students while using the stepped supporting tools. The results of the think-aloud study should on the one hand be used to improve the tool and on the other hand to assess whether the tools is suitable as a scaffold when solving tasks in organic chemistry. This led to the following research questions:

1. When do the stepped supporting tools support the problem-solving process of the students?
2. How should the stepped supporting tools be improved so that they can be used as suitable scaffolds by the students?
3. How can stepped supporting tools help students when constructing reaction mechanisms in organic chemistry?

In order to answer the research questions misconceptions of the students and other problems they have with the topics of the task are monitored and evaluated as well. It is for the development of the SST important to gain insights in the misconceptions and other problems our students have.

3.2 Design of the study

The study was conducted in summer 2018 in the course "Organic Chemistry" for non-major chemistry students. In this course 268 students were enrolled. However, only 50 – 60 % of the students participate regularly in the lecture and even less in the seminars. The different parts regarding the development and conduction of the study are described in detail below.

3.2.1 *The seminar and its students for the course "Organic Chemistry" for non-major chemistry students.*

The class "Organic Chemistry I" is designed for non-major chemistry students. The students study life sciences, nutritional science or geoecology as their major topic. 75 % of the students in the course in summer 2018 were female. Thematically, the course consists of an overview of the important substance families, including biomolecules, their synthesis and important reactions and their reaction mechanisms. 13 Seminars are held in which the lecture content is applied, practiced and consolidated. Different methods and materials are used. In addition, the students receive a homework sheet that included QR-Codes with additional assistance. Our survey (Hermanns & Schmidt, 2017) showed that only a small proportion of the students used the homework sheets. This increases the importance of the seminars as the most important learning opportunity for our students. A survey on the methods students used for learning showed they prefer especially simple methods as the marking of important words. More complex methods as for example concept maps are widely unknown. The same survey showed that the knowledge in organic chemistry consists mainly of the topics from grade 7 – 10 (Hermanns et al., 2017). Knowledge on reaction mechanisms and basic concepts for constructing them should therefore not be available. As a survey on the school curricula in Germany showed (Hermanns & Keller, 2019) only few mechanisms (mostly radical polymerization and / or substitution and the electrophilic aromatic substitution) and not in all federal states are taught in grades 11 – 13. For most of students that means that they are confronted with reaction mechanisms for the first time in our course.

3.2.2 *Expert rating in preparation for the study*

In preparation for the study the task and the stepped supporting tools were rated by experts (two PhD-students and one professor). The design of the stepped supporting tools was based on the experience of the author who used this method regularly at school as a chemistry teacher and on the literature to this topic (Hänze, Schmidt-Weigand & Stäudel, 2010; Hänze et al., 2010; Leisen, 2003; Hermanns et al. 2019). The stepped supporting tools had to be used because their assessment was the central aim of the evaluation. For this, the experts used an evaluation sheet (see Table 1). Free answers and suggestions for improvement were also possible. The results of the expert rating using a four-item Likert scale (strongly disagree (1) – strongly agree (4)) are shown in Table 1.

Tab. 1
Results of the expert rating of the task "electrophilic addition to the double bond"

Item	Arithmetic mean
The SST are arranged logically	4
The SST are formulated clearly	3.7
The SST explain the task	3.7
The SST are scaled correctly	3.7
The SST help to classify the exercise	4.0
The SST explain how to solve an exercise systematically	3.7

The design of the stepped supporting tools was rated as very good. Additional suggestions were made in form of advice regarding small errors, such as typographical mistakes, as well as suggestions of missing information. Formulations that had the potential to be misunderstood were reformulated.

3.2.3 *The task and its stepped supporting tools*

As task for the think-aloud study the electrophilic addition on the double bond was selected. This topic is part of the lecture and for many students hitherto unknown. The topic "alkene“" is part of the school curriculum in 10 of the 16 federal states in Germany. The reaction mechanism of the electrophilic addition is only in two states a topic of the school curriculum in grade 11-13. For most of our students this reaction mechanisms is therefore till the lecture unknown. (For the task and the SSTs: see Appendix 1).

The mechanisms for the electrophilic addition on the double bond is the first mechanism using the concept nucleophile-electrophile in the lecture and was therefore selected for this study. The task used in this study was a task of a former written exam and represents a common task in our lecture. After writing the products for the addition of H_2 and Br_2 with the cyclohexene and the educts (H_2O and HCl) for the electrophilic addition starting from two reaction products, the reaction mechanism for the reaction of H_2O with the cyclohexene using electron pushing arrows has to be formulated. For all elements of the tasks stepped supporting tools are available. These tools are printed on a piece of paper that is placed in a clear plastic sleeve and masked by a darker sheet of paper so that students can reveal each step one at a time (see Figure 1). One at a time, the stepped supporting tools are pulled out to the dividing line, without revealing the next tool.

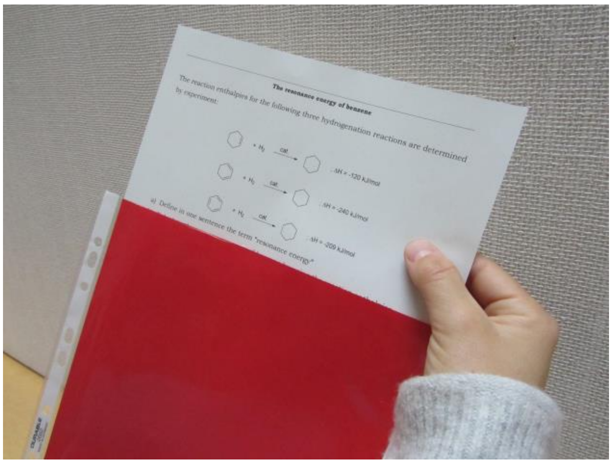


Fig. 1. *Stepped supporting tools in a clear plastic sleeve.*

3.2.4 *Recruiting of the test persons*

Test persons were recruited halfway through the semester. Students listed in the lecture to a brief presentation of the study, and those who were interested registered in a list containing appointments. 15 students were ultimately registered and 10 students (9f, 1 m) participated (the other students didn’t show for the study without giving a reason). The students received 20 Euros as compensation for their time. One student was studying geoecology, one student nutritional science and eight life sciences. Seven students were in their first year, two were in their second or third. The goal of the study and use of the data were explained to the students at the beginning of the study; ethical guidelines were followed. The approval of the institutional review board is not required at German universities.

3.2.5 *Conducting the think-aloud study*

At the beginning of the study, the workplace (see figure 2) was explained to the students: the recorder, the sheet with the task, the stepped supporting tools and additional paper for notes.

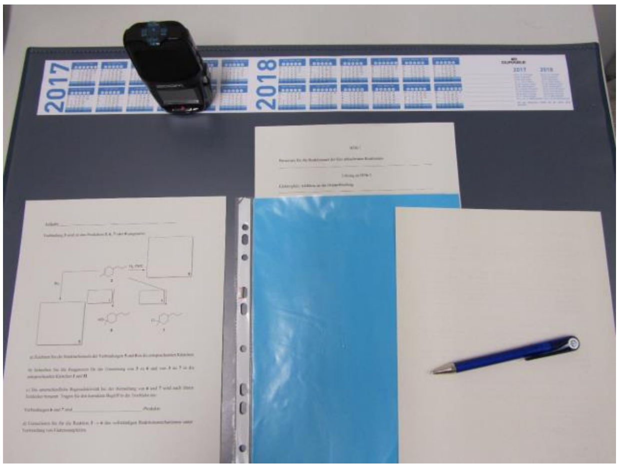


Fig. 2. *The workplace.*

To familiarize themselves with the think-aloud method, the students first solved a task naming an organic molecule before solving the real task. Students were asked to think aloud while naming a halogenated alkane with alkyl side chains.

After solving this task, the students received the real task of “electrophilic addition on the double bond” and the accompanying stepped supporting tools (nine in total) and began to solve the task. The students decided whether and when to use the SST. Only when they stopped speaking were they prompted to continue. Twice students were alerted to the availability of the SST. Once a student was reminded of the content of a tool to encourage the student to use this specific tool.

After completing the recording, both tasks were discussed with the students in order to ensure added value for the students’ participation. The records and the students’ notes were available for the analysis of the think-aloud study.

3.2.6 *Analysis of the think-aloud study*

The records were transcribed (the time spent working on the tasks was between 10 minutes 27 seconds and 21 minutes 8 seconds) and subsequently manually coded with colored pens. The codes serve first and foremost as an orientation to the transcripts. An overview of the coded categories and some examples are given in table 2.

Tab. 2
Overview of the categories with examples from the transcripts

Category	Example from the transcripts
Comments that do not belong to the task or to solving the task	*I could now use my green pen, which I use in the lectures*
Reading of the task (exact wording of the task)	
Reading of the SST (exact wording of the SST)	
Reading of the solution (exact wording of the solution)	
Solving the task while using the SST	*….the catalyst is added here*
Solving the task without using the SST	*Well, we start with compound three. Any ring with side chains. Then we add bromine*
Misconceptions or missing specialized knowledge	*I added the positive charge at the wrong end*
Comments that do belong to the task or to solving the task	*Are these all tasks? I can manage this, right?*

The coding was carried out again by an expert using the coding manual. The intercoder reliability according to Brennan and Prediger (1981) was 83.6 % and therefore sufficient. The transcripts were evaluated according to Kuckartz (2016) using the method of qualitative content analysis.

The parts of the transcripts that belonged to the category "solving the task while using the SST" were used for answering the research questions. For every research question all separate steps of the SSTs were analysed in detail. In addition, the notes of the students that they made while solving the task were also taken into account.

For this publication, the task, the stepped supporting tools and all examples were translated from German to English.

4 RESULTS AND DISCUSSION

The task on the naming of a molecule, which was used as a warm-up task, was solved correctly by six students. The others incorrectly chose either the numbering or the sequence of the side chains. The result of this task was not commented on or discussed, because the aim was to get used to thinking aloud and the students should not have been unsettled before solving the actual task.

The difference in the processing times and when solving the numbering task already shows that the students had different requirements regarding reading competence, methodological approach and specialist knowledge. A detailed evaluation of the transcripts is carried out below based on the research question.

4.1 Misconceptions and other problems

In all transcripts different misconceptions and other problems regarding organic or general chemistry arise. In our study three categories can be identified (see table 3).

4.1.1 *Problems with the bond line notation*

Especially atoms that are now drawn, as the H-atom at the double bond, were not recognized. This led for example to the statement *"the double bond cannot simply disappear while nothing is added"* by task a, where the products for the addition of Br_2 resp. H_2 should be written down. Although we encourage the students to use another style of writing if they have problems with the bond line notation, this opportunity was not used by all students, although one student expressed the not-understanding (*"I don't get it"*). This student just did not grasp that the notation was responsible for the not-understanding. A reflection on the own learning did therefore not take place. In future, teaching this topic should made transparent. In addition the students should actively learning methods to overcome this problem, as for example the method "mapping" as described by Flynn and Featherstone (2017). This strategy helps students to keep track of atoms and electrons while drawing a mechanism, but could also be used when writing down reaction products. Another method to introduce the bond line notation is described by Rios and French (2011). The students studied the bond-line structures belonging to pleasant-smelling molecules and translated the bond-line structures into Lewis-structures.

4.1.2 *Problems with the specialist language*

Students often use the wrong term, as for example "atom" when meaning "molecule" (*"water atom"*). Although most students had chemistry at school and the course in general chemistry at university was already completed, their specialist language especially regarding contents in general chemistry was sloppy. A connection between using a correct language (or not) and their comprehension of the topic was not made. This can be seen as another indication of insufficient reflecting on the own learning process. Reflection should therefore be an integral part of the lecture and the seminars, regardless of the time required. In the lecture, small tasks on reflection could be integrated, for example by using a digital tool. Metacognition is important in learning chemistry as described by Rickey and Stacy (2000): "good monitoring and regulation of thinking can improve success in problem solving". With regard to the problems with the specialist language Nakhleh (1992) writes, that "educators should help students begin to understand the differences between atoms, molecules, and ions. Students should be reminded that if they can't explain a concept in molecular terms, then they really don't understand it".

This supports our argument that sloppy use of technical language prevents learning.

4.1.3 *Inaccurate or false explanations and knowledge gaps*

The topics from general chemistry (*"C?"*) and from the ongoing course on organic chemistry (*"Electrophilic. That means it is negative"*) are often not known or understood. The students should actively and independently learn the contents of the lecture, but mostly they don't do this during the time of the lecture. Most students start learning when the written exam is due which is in our course three months after the last lecture. For our seminars, this means that we have to communicate more transparently which knowledge the students need for solving the tasks. Additionally this knowledge must be made available, for example in the SST.

Tab. 3
Overview of the misconceptions and other problems of the students while solving the task with examples from the transcripts

Misconceptions and problems	Examples from the transcripts
Problems with the bond line notation	*"It's just gone. I don't get it. When hydrogen is added to a double bond, an alkane is formed. The double bond cannot simply disappear while nothing is added"* (from transcript 3)
Problems with the specialist language	*"…but a new water atom"* (from transcript 3) *"The acid, the H atom"* (from transcript 9) *"either radical or jesenophilic"* (from transcript 10)
Inaccurate or false explanations and knowledge gaps	*"Electrophilic. That means it is negative"* (from transcript 3) *"I tied the positive charge to the wrong end"* (from transcript 10) *"C?"* (from transcript 2) *"I don't know yet what a catalyst is"*. (from transcript 8)

4.2 Research questions

All research questions will be discussed below. Excerpts from the transcripts are given.

4.2.1 Research question 1. When do the stepped supporting tools support the problem-solving process of the students?

If tasks are designed with SST, these must be used by the learners if they are to be effective in learning. The evaluation of the transcripts shows that the SST are used differently by the students. Seven students used them, as intended, as assistance, four students initially solved some of the tasks independently and then used the corresponding SST to check their answers. However, all students used to some extent the SST for support. This observation fits in with the students' assessment of their use of the SST as reported by Hermanns et al. (2019).

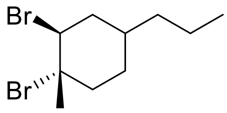
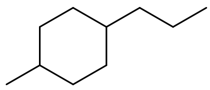
For answering research question 1 the transcripts belong to the use of the stepped supporting tools 1-6 were analysed. An overview of the SST, their solutions and didactic goals is shown in table 4.

The first SST was used by five students as support. Two students did not have the sufficient previous knowledge to understand the tool as the excerpts from the transcripts show: *"Reaction type? Doesn't mean anything to me"* and *"Oh, oh, oh. I don't know that"*. The tool cannot help here, because the technical term is unknown to the students. The students however read the solution immediately without taking some time to think properly. Analyzing the term should have given them some idea what the tool meant. The other three students did get some idea of the reaction type, but neither said the correct solution. One student also didn't reflect on the wording "reaction type": *"Anyway, there's a catalyst, I think. Once the hydrogenation at 8 and the bromination at 5. Could also be the radical bromination or something similar."* Compared to the previous ones some idea of the reaction that occurs was expressed. Similar statements could be observed with the other students: *"Halogenic addition it is called, I think. But I'm not certain."* And *"It's bromination then"*. After reading the solution, three students simply accepted it: *"So"* or *"Okay"*. Two students definitely didn't see that the reaction type was similar for all reactions (addition on the double bond); they referred only to one part of the task: *"This is now, I think compound five"* and *"Yes. That's here, I would say. Now I look to eight"*. Due to lack of prior knowledge or insufficient reflection on the own problem solving process, this SST could not help the students as intended by the didactic goal.

SST 2 focusses on the stereochemistry by the electrophilic addition of bromine on the double bond.

This tool was used by three students. The tool didn't help, because they didn't know what the term "backside attack" meant: *"I don't even know what a backside attack is"*. Here also the lack of prior knowledge from the lecture prevented the help from the tool as intended. However, as with SST 1 no deeper thought was given to the term "backside attack". The word "backside" could have been understood as a hint for stereochemistry. The term or its significance were apparently unknown to all students in the study, because neither student, also those who didn't use the SST, solved this part of the task correctly. The three students, who used the tool, read the solution to the tool afterwards. But not even the solution solved the problem with the term: *"I'm still not sure what a backside attack is. […..] Only it's just in the front and in the back"*. The solution was once simply accepted: *"Now I have here the solution. Okay, then I'll keep looking"*. The importance of the stereochemistry in this reaction was not recognized: *"The solution looks similar except that I didn't pay attention whether it is attached in front or behind"*. Here again missing reflection can be observed; the didactic goal was not reached.

Tab. 4
Stepped supporting tools 1-6

Nr.	Stepped supporting tool	Solution	Didactic goal
1	Name the reaction type of the reactions taking place here.	Electrophilic addition to the double bond.	The students should recognize that all reactions in the task are the same, namely electrophilic additions.
2	During the addition of bromine, a so-called backside attack takes place. Consider this in the structural formula of the product. Note compound 5.		The wording “backside attack” should trigger thinking about stereochemistry.
3	When hydrogen is added to a double bond, an alkane is formed. Note compound 8.		The SST says which reaction occurs and additionally should the wording “alkane” make clear that the product is saturated.
4	Compare compounds 3 and 7 and note the new atoms added in compound 6 after addition. What chemical compound was obviously added here? Note this compound in the left box (I).	The compound is H_2O (Added: 1 OH, 1 H resp. 2 H and 1 O).	The counting of the atoms should ensure that the students did not forget some atoms, which happens often because of the problems with the bond line notation.
5	Compare compounds 3 and 7 and note the new atoms added in compound 7 (after addition). What chemical compound was obviously added here? Note this compound in the right box (II).	The compound is HCl (Added: 1 H und 1 Cl).	As in 4.
6	The addition of asymmetric molecules such as H_2O or HCl can produce two different regioisomers. A regioisomer is preferred because it proceeds by a more stable intermediate stage. This product is named after its discoverer.	Markovnikov	Besides the information of the SST on regioselectivity, the word “Markowniko3” should trigger the memory because the rule of Markovnikov should be known from the lecture.

The SST 3 addresses an apparently uncomplicated task: the addition of hydrogen to the double bond. The chemical family of the product, alkanes, is also named in the tool. The tool was used as support by six students. One reason from this increase in use of the SST could be that the students noticed that it would be a good idea to use the SST as they were no completely successful in solving the first part of the task. From the six students who used the SST three students solved the problem correctly: two noted the H-atoms (see figure 3) and one student not; the molecule was completely written in bond-line notation.

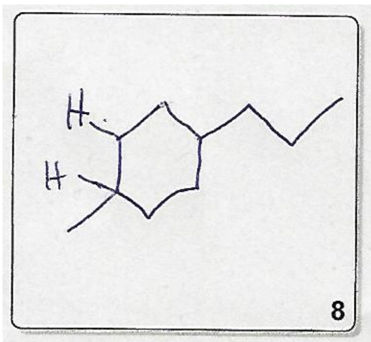


Fig. 3. *Solution for compound 8 (from transcript 7).*

The mixing of two notation styles as shown in figure 3 is problematic; it would be better to use either the bond line notation or the Lewis structure. However, the cognitive load for the students when constructing Lewis structures is relatively high (Tiettmeyer et al. 2017), because the construction consists of at least six steps. Changing between notations should therefore be practiced in the seminars. The reason for drawing Lewis structures, namely to use those structures for predicting chemical and physical properties (Cooper, Williams and Underwood 2015) should be discussed as well.

One student read the SST but didn't pursue the task. One student wrote the wrong product; only a line was added. Two mistakes were made here: only one atom was added and this atom was not written, but wrongly a line which means a methyl group. One student read the solution directly without trying to solve the problem on this one. The whole reaction was not understood as the quotation from the transcript shows: *"Yes, that is an alkane, when there is no longer a double bond, a cycloalkane. Okay. It's just gone. Okay. That I don't understand"*. This not-understanding is apparently due to the problems with the bond-line notation. This SST was therefore only helpful when some understanding and knowledge on the current topic and different notation styles were available.

The SST four and five should help the students solve a kind of task that is customary in the written exams where a missing educt or product should be added. Six students used the SST for these two tasks. Of the six students, two students solved both tasks by using the SST correctly. However, one student named the HCl hydrochlorid acid and not hydrogen chloride. The other four students solved only one task (either the addition of H_2O or HCl). One student noted the H_2O molecule correctly, but could not transfer this solution to the new problem, the addition of HCl. There the student wanted to add chlorine: *"Yes, there was a hydroxid group added. Double bond was split again. So just add OH minus. But then there's the charge. I'm sure it has to be H_2O. The same then probably for two. Chlorine has been added"*. The other students did not see that H_2O was added, but could solve the second task. They were able to use the solution of the first problem to solve the second task (addition of HCl): *"So obviously OH minus was added. There, but that can't be it. First, OH always has a charge, namely negative, and second I cannot imagine how an OH minus reacts with the double bond so that the double bond disappears and no negative charge ….. Let's look at the solution. The compound H_2O has been added. [….] c. HCl. Same principle"*. The SST helped the students in solving at least one example; they understood the principle of the addition to the double bond from the beginning or from the addition of the H_2O. Overall the SST were helpful; the didactic goal was mostly achieved. The two students who did not use the SSTs solved both tasks correctly.

The SST 6 was designed as a trigger for the name "Markovnikov". In written exams sometimes small tasks that only test knowledge learned by heart are included. This SST is therefore not suitable to positively influence the problem-solving process; no problem-solving occurs here. Either the student know or they don't. This task was included because it belonged to the original task from a written exam. However, the transcripts of the think-aloud study gave here some interesting insight in the learning of the students. One students suspected that the name askes for could be "Markovnikov". All other students didn't know the name. One student thought that he didn't know it because he wasn't in the lecture as this topic was discussed: *"I probably missed class"*. Obviously he thinks that being in the lecture is sufficient for knowing the topics. Another student argued similarly: *"Names. We didn't have names today"*. If the students really think being in a lecture is sufficient for their learning that would be an explanation why they don't review and study the topics of the lecture in their own time. One student however understood that the answer is a name: *"Do you want to know the name of the discoverer?"* Three students didn't grasp that the answer should be a name. There solutions were: Intermediate products, addition products and regioisomer. One student even hold to the wrong answer after reading the solution: *"Is the answer then that they are Markovnikov products? But they were intermediate products. So I wasn't even that wrong"*. Here again no reflection on the own actions took place.

Summarizing, the students could often not make constructive use of the stepped supporting tools because they don't have sufficient problem solving skills. This is a bit unexpected, because the students have many opportunities for gaining those skills: by visiting the lectures and seminars and by the homework we provided for our students. Four methods of teaching problem solving skills are mentioned by Gilbert (2008): by example (like we do in the lectures and seminars), by homework problems (as also provided by us), by quizzes and exams (such elements are part of our seminars) and by laboratory experience. This later method is for our students no option because for organizational reasons their practical work in the laboratory takes place a few months after the lecture and the seminars.

When evaluating the transcripts we observed that the students often don't try different approaches when solving a problem or even don't try at all. The importance of trying something and repeatedly trying are mentioned by Bodner and Domin (2000). We observed, although the students could start from scratch with every supporting tool they received, that even those opportunities were seldom used. However, the students who had sufficient previous knowledge and basic skills in problem solving were supported by the tools.

4.2.2 Research question 2. How should the stepped supporting tools be improved so that they can be used as suitable scaffolds by the students?

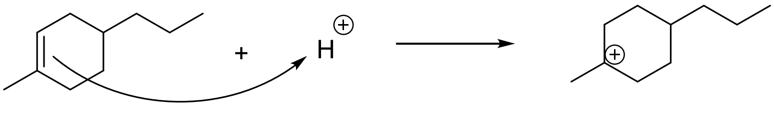
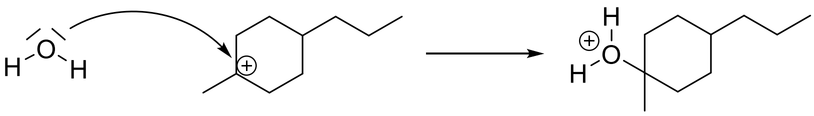
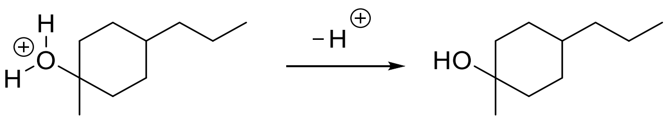
As discussed in research question 1 not all students could benefit from the tools as intended. A lack of prior knowledge and methodological competence in the field of problem solving was a hindrance. The new tool should therefore provide this knowledge and give methodological support in order to solve the problem as well as building up problem solving competences. The tools should therefore provide three different categories of support: strategy (methodological approach for solving the task and to build up problem solving competences), knowledge (the prior knowledge that is needed to solve the task) and application (opportunities to apply the knowledge needed for the task at hand). Strategy knowledge for problem solving is described by Wüstenberg, Stadler, Hautamäki & Greiff (2014). They used the vary-one-thing-at-a-time strategy. This approach is quite similar to the task navigator which also gives one strategical tip at a time as for example: “Read the task and note the most important terms of the task”. For meaningful learning a student must have some relevant prior knowledge (Bretz, 2001). If the student lacks those knowledge, the task navigator provides it, as for example: “By the electrophilic addition the positively charged particle attacks”. This knowledge should then be applied to gain new knowledge and therefore learn meaningfully. An example for an application tip is: “Note, which positively charged particle attacks in this example and where this particle comes from”.

Those new tools should be embedded in a holistic approach that is used in the lectures, the seminars, the laboratory and the written exam at the end of the course. For this new approach we use the acronym STRAKNAP (STRAtegy – KNowledge – APplication). For the development of the new tools all three categories have to be transparent while using the tools. We therefore choose a color code for these new tools. The strategic tools are printed in black, the tools providing the knowledge in red and the application tools in blue. First results with these new tools will be published in due course.

4.2.3 Research question 3. How can the stepped supporting tools help students when constructing reaction mechanisms in organic chemistry?

For answering research question 3 the transcripts belonging to the use of the stepped supporting tools 7 – 9 were analysed. An overview of the SST, their solutions and didactic goals is shown in table 5.

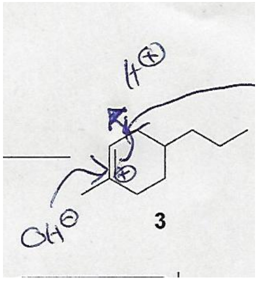
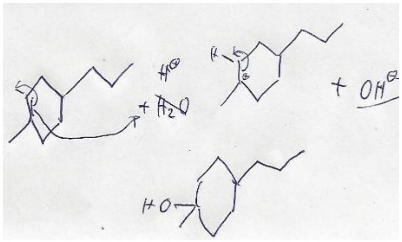
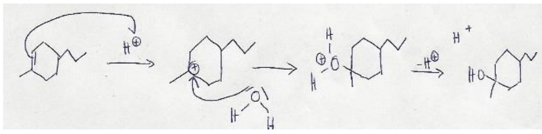
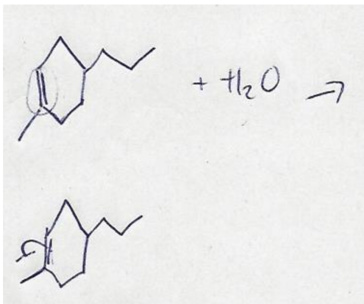
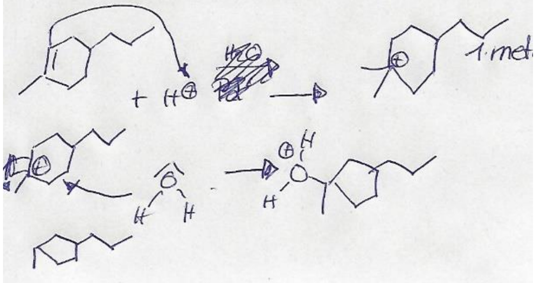
Tab. 5
Stepped supporting tools 7 – 9

Nr.	Stepped supporting tool	Solution	Didactic goal
7	In the first step, the catalyst attacks the double bond of compound 3. Note the catalyst and draw an electron arrow from the double bond to the catalyst.	 3	This SST should ensure the correct approach to the task. The students should recognize that one C-atom is positively charged.
8	In the second step, the water molecule attacks the positively charged carbon atom. Draw the electron arrow correctly!		The request of drawing an electron arrow should ensure that the students think about the direction of the arrow. Also, should the students see where the positive charge is after the addition of the water molecule.
9	In the last step, the catalyst is cleaved off again. Note the structural formula of the final product.	 6	The students should remember that H^+ was the catalyst and write the product without the charge.

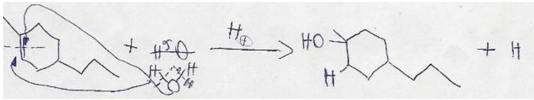
After reading the task "Formulate the complete reaction mechanism for the reaction from 3 to 6 using electron arrows" only three students read the SST 7 immediately. Seven students started the task without using the SST. A summary of the analysis of all transcripts is shown in table 6.

Tab. 6

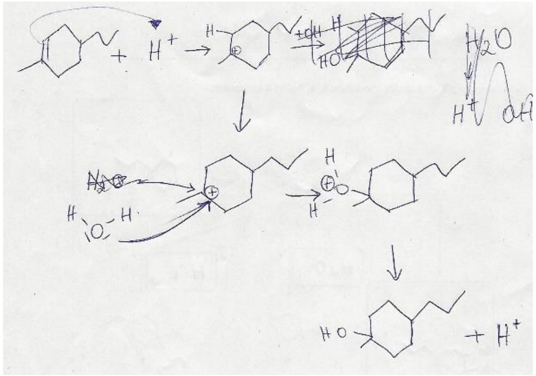
Analysis of all transcripts on the construction of the reaction mechanism

Nr.	How students proceeded in constructing the mechanism and an analysis of their use of the SSTs.	Example from the manuscript
1	The SST 7 was read, but the term "catalyst" was unknown. After reading the solution, H^+ (from the water molecule) was added and then immediately OH^-. The SST 8 was not understood, but accepted. The student stopped there. After the hint that there is one other SST this was read. As a solution the cleavage of two H-Atoms or the addition of H_2 were discussed. The solution to SST 9; the separation of H^+ was taken for granted. No reaction mechanism (in several steps) was formulated as shown by the example in the right column.	
2	The student started without reading the SST. First H^+ (from the water molecule) was added and then OH^-. After reading the solution, the comment was "*a H_2O-atom is added, not OH^-*". However, this part has not been corrected. The solution to SST 9, that the H^+ is cleaved off, was simply accepted. As shown in the example, the construction of a reaction mechanism in several steps remains rudimentary.	
3	The SST 7 was read, but the term "catalyst" was unknown. Also that H^+ can be a catalyst: *"H^+ is a catalyst? Okay. That's new for me. But okay."* The steps of the mechanism were copied by using the solutions, but clearly not understood: *"I ask myself, how the water can add there so easily."* The separation of the H^+ however was seen immediately and written down independently by the student as the last step.	
4	After reading the task, the cyclohexene was drawn. The first SST was then read. The idea that H^+ should be the catalyst was said, but it was unclear what happened after the addition. After reading the solution, it was not understood, why one C-atom had a positive charge. The second SST was read, but it was not tried out. Some hopping between different SSTs took place. The solution was read and then the SST 8: *"But now it looks as if the oxygen atom is positive".* After some further hopping between the SSTs and the different parts of the tasks the student stopped. The last SST was not used. The reaction mechanism was not written at all, even not after reading the first two solutions.	
5	The task and the SST 7 were read. The solution was written. After reading SST 8 the water molecule was added correctly. The cleavage of the catalyst however was not done. "Note the structural formula of the product" was wrongly interpreted by the student; the name of the product was formulated. The solution was then read and commented with *"Okay. Good."* The last step of the mechanism was not written down after reading the solution.	

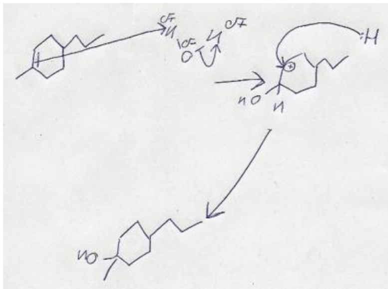
6 The task was started, but without constructing the reaction mechanism. After some time, the first SST was read. *"Okay. What would be the catalyst? That's the question here."* The solution was read: *"Oh. It was meant that I do this step by step".* It was obviously not clear what constructing a reaction mechanism meant. After reading the next SST the water molecule was added. It became then clear that something should be split off: *"There must an H be split off."* It was here not clear that the H^+-Ion should be split off. The student did not realize that the solution was incorrect even after reading the solution: "*Okay. I just did that. Good."*



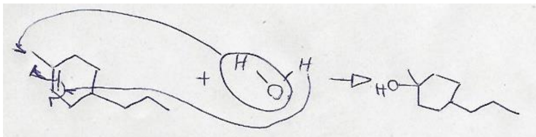
7 The SSTs were used. After reading SST 7 an H^+ was added. After that OH^- was added. After reading SST 8 this was corrected and a water molecule was added: *"Then it binds and a positive charge is created – continues to exist".* After reading the last SST the H^+ was split off: *"then hydrogen was the catalyst."*



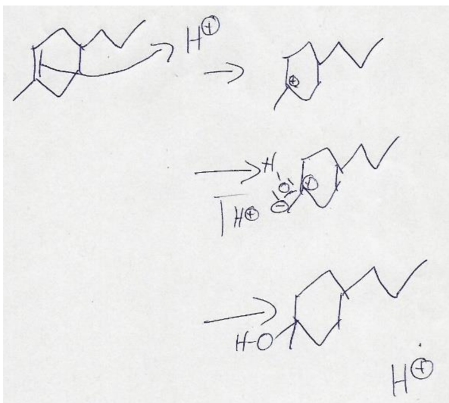
8 The student constructed the reaction mechanism without using the SST: an OH particle (from a water molecule) was added and the other C atom received a positive charge. This was then neutralized by adding an H atom (with two electrons – apparently from the water molecule: *"The electrons in the water then go away to the other hydrogen"*).Afterwards SST 7 was read: *"I don' know now what a catalyst is. I 'll let it go."* Because the solution was not read by the student, no learning progress was achieved. Also there was no reflection. Although the first tool was not understood, the other SSTs were not used.



9 The student started with the mechanisms without reading SST 7. The water molecule was divided in an OH and an H part. This was described as following: *"OH goes over there and adds there…." "The H^+ alone goes there."* The SST 7 was read afterwards and commented: *"Catalyst. That should be a peroxide".* After reading the solution however no corrections were written down. The addition of the water molecule (SST 8) was not drawn. The student thought it was not possible, because the oxygen would be positively charged. The H^+ as being the catalyst was commented with: *"An acid is probably not contained in the peroxide."* Again, there was no reflection; the own solution was not compared with the solutions of the SSTs.



10 SST 7 was read. After some time an acid as catalyst was identified. Before writing down the first step however there was some hopping between the different parts of the tasks. After reading the solution to SST 7 the water molecule was divided in OH^- and H^+. The student assumed then that the task was solved. After prompting to also use the other SSTs this was done. The solution was compared with the own solution: *"I shouldn't have split up the water."* Here some kind of reflection took place.



Summarizing, it can be concluded that, with sufficient prior knowledge, the SSTs helped the students in constructing the reaction mechanism. The SSTs 7-9 give clear and specific instructions what the students should do at the molecular level, as for example “draw the electron arrow”. This support was therefore used more successfully by the students than the SSTs 1-6. These tips included especially support for noting the correct reaction product as in SST 3: “when hydrogen is added to a double bond, an alkane is formed. Note compound 8.” The SST 7 pointed out that in the first step the catalyst attacks the double bond. Almost all students started their reaction mechanism with the addition of H^+. Unfortunately, the majority took the proton from the water molecule. It was obviously not clear that the autoprotolysis of water cannot provide enough H^+-ions to catalyze this reaction and that a catalyst is a particle that is split off in the last step of a reaction mechanism. This led to the second error; instead of adding water in the second step the hydroxide ion was added. After reading SST 8 three of the students corrected their approach. The SST steered them in the right direction. For those students the last SST was also helpful: the catalyst was split off. Those students who took the proton from the water molecule did not add a catalyst and had therefore nothing to split off. Unfortunately, they did not reflect on this difference and took the solution for granted. Ultimately, it can be concluded that the supporting tools are helpful when the reaction mechanism is constructed systematically and when the students reflect on their own approach.

4.3 Limitations

The study was conducted with ten students who voluntarily participated. It is not possible to oblige students in attending the study. However, the students who participated can be regarded as a suitable cross-section. They were known to us from interactions in the course and their performance can be classified on an average level. From the results of exams during different courses, we know this to include the majority of the students. Therefore, we think that the results can be generalized. Students who don’t need SST were of less interest for this study, because we wanted to know whether our SSTs are helpful.

5 CONSEQUENCES AND OUTLOOK

For future use of the SST in seminars, these should be developed further as task navigators as discussed before. The new name was chosen because the wording “supporting” had the consequence that the students initially wanted to solve the problem without help and were very often not successful when using this approach. The more neutral wording “navigator” prevents this behaviour as we observed in our seminars. Because the students often lack prior knowledge and the required methodical competences for solving tasks in organic chemistry, these navigators should provide the required knowledge, methodical strategies and support for the task at hand. To ensure this, it was important that the students used the navigator to get the different types of support: strategy (methodological approach for solving the task and to build up problem solving competences), knowledge (the prior knowledge that is needed to solve the task) and application (opportunities to apply the knowledge needed on the task at hand). First task navigators are developed and used in our seminars. An evaluation with questionnaires and a thinking-aloud-study were conducted. The results are currently being analysed and will be published in due course. In addition, the students should be encouraged to reflect on their own actions. Suitable tools to enable the students to reflect in the seminars are currently under development and will be implemented and evaluated in the next course.

ACKNOWLEDGEMENT

I thank

- the Potsdam Graduate School (POGS) for financial support.
- Prof. Dr. Bernd Schmidt (University of Potsdam) for the use of his tasks.
- all participants of this study.
- Hilke Schulz for technical support with the layout of this paper.

REFERENCES

Bhattacharayya, G. & Bodner, G.M. (2005). It gets me to the product: how students propose organic mechanisms. *Journal of Chemical Education*, 82 (9), 1402-1407.

Bowen, C. W. (1994). Think-Aloud methods in chemistry education. *Journal of Chemical Education*, 71 (3), 184-190.

Brennan, R. L. & Prediger, D. J. (1981). Coefficient Kappa: Some uses, misuses, and alternatives. *Educational and Psychological Measurement*, 41, 687-699.

Bretz, S. L. (2001). Novak’s theory of education: human constructivism and meaningful learning. *J. Chem. Educ*., 78 (8), 1107-1116.

Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P. & Glaser, R. (1989). Self-Explanations: How students study and use examples in learning to solve problems. *Cognitive Science*, 13, 145-182.

Cooper, M. M. & Klymkowsky, M. (2013). Chemistry, Life, The Universe, and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform. *Journal of Chemical Education*, 90 (9), 1116-1122.

Cooper, M. M., Williams, L. C. & Underwood, S. M. (2015). Student understanding of intermolecular forces: a multimodal study. *Journal of Chemical Education*, 92 (8), 1288-1298.

Cooper, M. M. & Stowe, R. L. (2018). Chemistry education research – from personal empiricism to evidence, theory, and informed practice. *Chemical Reviews*, 118 (12), 6053-6087.

Ericsson, K. A. & Simon, H. A. (1993). *Protocol analysis: Verbal reports as Data*. MIT Press, Cambridge, UK.

Fach, M., de Boer, T. & Parchman, I. (2007). Results of an interview study as basis for the development of stepped supporting tools for stoichiometric problems. *Chemistry Education Research and Practice*, 8 (1), 13-31.

Flynn, A. B. & Ogilvie, W.W. (2015). Mechanisms before reactions: A mechanistic approach to the organic chemistry curriculum based on patterns of electron flow. *Journal of Chemical Education*, 92 (5), 803-810.

Flynn, A. B. & Featherstone, R. F. (2017). Language of mechanisms: exam analysis reveals students' strengths, strategies, and errors when using the electron-pushing formalism (curved arrows) in new reactions. *Chemistry Education, Research and Practice*, 18, 64-77.

Fromman, U. (2019). *Die Methode „Lautes Denken"*[the method „thinking-aloud"]. https://www.e-teaching.org/didaktik/qualitaet/usability/Lautes%20Denken_e-teaching_org.pdf (accessed Oct 2019)

Grove, N.P., Cooper, M. M. & Rush, K. M. (2012a). Decorating with arrows: toward the development of representational competence in organic chemistry. *Journal of Chemical Education*, 89 (7), 844-849.

Grove, N. P., Cooper, M.M. & Cox, E.L. (2012b). Does mechanistic thinking improve student success in organic chemistry? *Journal of Chemical Education*, 89 (7), 850-853.

Grove, N. P. & Bretz, S. L. (2012c). A continuum of learning: from rote memorization to meaningful learning in organic chemistry. *Chemistry Education Research and Practice*, 13, 201-208.

Hänze, M., Schmidt-Weigand, F. & Stäudel, L. (2010). *Gestufte Lernhilfen in der Sekundarstufe II. Einsatzmöglichkeiten und pädagogische Bedeutung* [stepped supporting tools in upper school] in Boller, S., Lau, R. (Ed.): Individuelle Förderung durch innere Differenzierung. Praxishandbuch für Lehrerinnen und Lehrer der Sekundarstufe II Weinheim, Germany.

Hermanns, J. & Schmidt, B. Zur Verwendung von QR-Codes in Uni-Seminaren – ein Baustein in den neu konzipierten Übungen zur Vorlesung „Organische Chemie für Studierende im Nebenfach" [The use of QR-Codes in seminars – a building block in the newly designed seminars for the course "organic chemistry" for minor students], *CHEMKON*, 2017, 24 (3), 139-141.

Hermanns, J. & Keller, D. (2019a). School-related content knowledge in organic chemistry – the influence of different school curricula on the development of tasks. *Progress in Science Education*, 2(1), 17-27.

Hermanns, J. & Schmidt, B. (2019b). Developing and applying stepped supporting tools in organic chemistry to promote students' self-regulated learning. *Journal of Chemical Education*, 96 (1), 47-52.

Hilton, A., Nicols, K. & Gitsaki, C. (2019). *Scaffolding chemistry students' learning within the context of emerging scientific research themes through laboratory inquiry*. https://www.researchgate.net/publication/43525559_Scaffolding_chemistry_students'_learning_within_the_context_of_emerging_scientific_research_themes_through_laboratory_inquiry.

Jeon, K., Huffman, D. & Noh, T. (2005). The Effects of Thinking Aloud Pair Problem Solving on High School Students' Chemistry Problem-Solving Performance and Verbal Interactions. *Journal of Chemical Education*, 82 (10), 1558-1564.

Kuckartz, U. (2016). *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung*. Beltz, Weinheim und Basel, Germany and Switserland.

Leisen, J. (2003). *Methoden-Handbuch deutschsprachiger Fachunterricht* [Methods handbook on German subject teaching], Varus, Bonn, Germany.

Livengood, K., Lewallen, D. W., Leatherman, J. & Maxwell, J. L. (2012). The use and evaluation of scaffolding, student centered-learning, behaviorism, and constructivism to teach nuclear magnetic resonance and IR spectroscopy in a two-semester organic chemistry course. *Journal of Chemical Education*, 89 (8), 1001-1006.

Nakhleh, M. B. (1992). Why some students don't learn chemistry – Chemical misconceptions. *Journal of Chemical Education*, 69 (3), 191-196.

Rickey, D. & Stacy, A. M. (2000). The role of metacognition in learning chemistry. *Journal of Chemical Education*, 77 (7), 915-920.

Rios, A. C. & French, G. (2011). Introducing bond-line organic structures in high school biology: an activity that incorporates pleasant-smelling molecules. *Journal of Chemical Education*, 88 (7), 954-959.

Someren van, M. W., Barnard, Y. F. & Sandberg, J. A. C. (1994). *The think aloud method – a practical guide to modelling cognitive processes.* Academic Press, London, UK, 1994. https://www.researchgate.net/publication/215439100_The_Think_Aloud_Method_-_A_Practical_Guide_to_Modelling_CognitiveProcesses (accessed Nov 2019)

Taber, K. (2002). *Chemical misconceptions: Prevention, diagnosis and cure*. Theoretical background, Volume 1 Royal Society of Chemistry, UK. (Buch).

Tiettmeyer, J. M., Coleman, A. F., Balok, R. S., Gampp, T. W., Duffy, P. L., Mazzarone, K. M. & Grove, N.P. (2017). Unraveling the complexities: an investigation of the factors that induce load in chemistry students constructing Lewis structures. *Journal of Chemical Education*, 94 (3), 282-288.

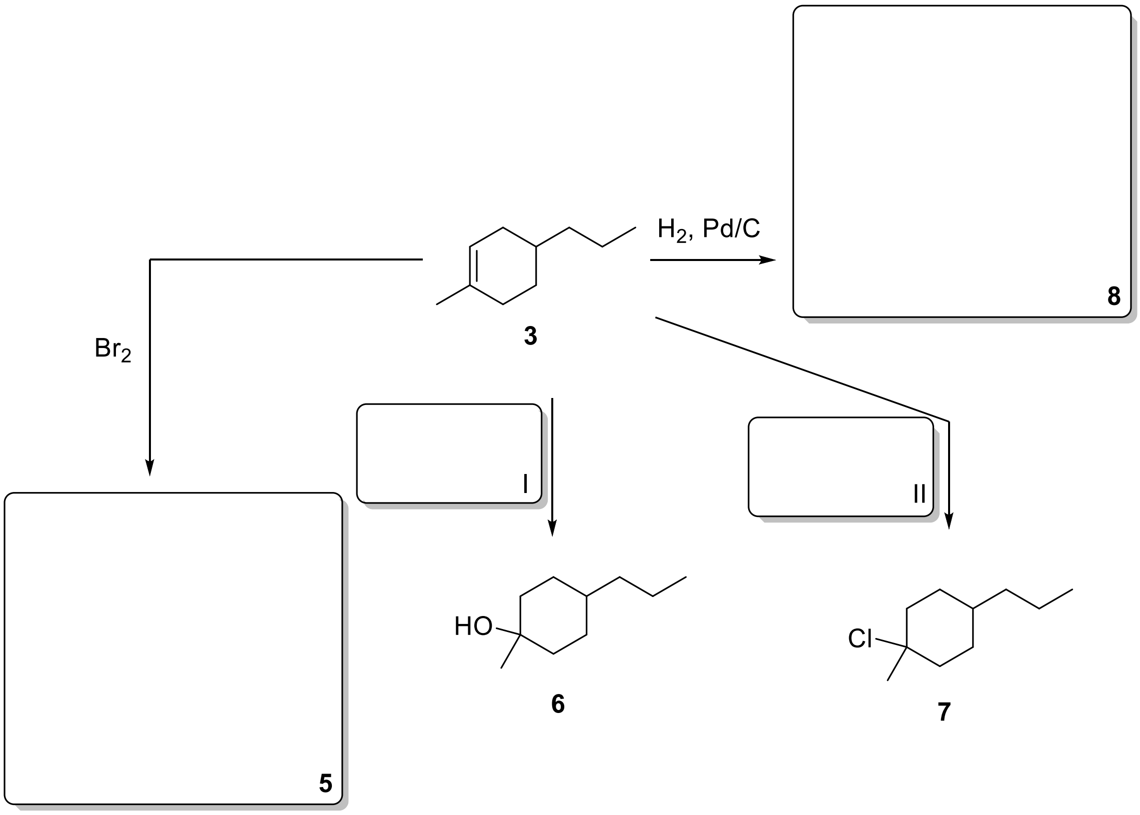
Wüstenberg, S., Stadler, M., Hautamäki, J. & Greiff, S. (2019). The role of strategy knowledge for the application of strategies in complex problem solving tasks. *Technology, Knowledge and Learning: Learning mathematics, science and the arts in the context of digital technologies,* 19*(*1-2), 127–146.

APPENDICES

Appendix 1: The task and the stepped supporting tools

Task

Compound **3** is converted to products **5**, **6**, **7** oder **8**:



a) Draw the structural formulas of compounds 5 and 8 in the corresponding boxes.

b) Note the reagents for the conversion from 3 to 6 and from 3 to seven in the corresponding boxes I and II.

c) The different regioselectivity in the production of 6 and 7 is named after its discoverer. Enter the correct term in the text gap:

Compounds **6** and **7** are ________________________________-products

d) Formulate the complete reaction mechanism for the reaction from 3 to 6 using electron arrows.

Stepped supporting tools:

SST 1

Name the reaction type of the reactions taking place here.

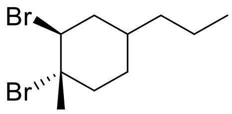
Solution to 1

Electrophilic addition to the double bond.

SST 2

During the addition of bromine, a so-called backside attack takes place. Consider this in the structural formula of the product. Note compound 5.

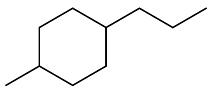
Solution to SST 2



SST 3

When hydrogen is added to a double bond, an alkane is formed. Note compound 8.

Solution to STT 3



SST 4

Compare compounds 3 and 7 and note the new atoms added in compound 6 after addition. What chemical compound was obviously added here? Note this compound in the left box (I).

Solution to STT 4

The compound is H_2O (Added: 1 OH, 1 H resp. 2 H and 1 O).

STT 5

Compare compounds 3 and 7 and note the new atoms added in compound 7 (after addition). What chemical compound was obviously added here? Note this compound in the right box (II).

Solution to STT 5

The compound is HCl (Added: 1 H und 1 Cl).

STT 6

The addition of asymmetric molecules such as H_2O or HCl can produce two different regioisomers. A regioisomer is preferred because it proceeds by a more stable intermediate stage. This product is named after its discoverer.

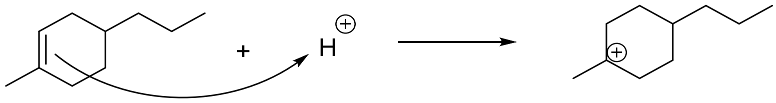
Solution to STT 6

Markovnikov.

STT 7

In the first step, the catalyst attacks the double bond of compound 3. Note the catalyst and draw an electron arrow from the double bond to the catalyst.

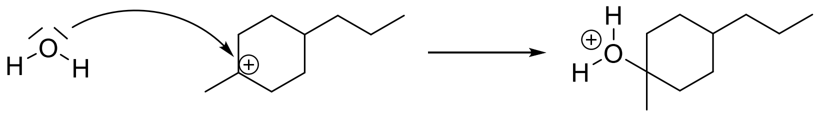
Solution to STT 7



STT 8

In the second step, the water molecule attacks the positively charged carbon atom. Draw the electron arrow correctly!

Solution to STT 8



STT 9

In the last step, the catalyst is cleaved off again. Note the structural formula of the final product.

Solution to STT 9