Animating the Intermediate: Design and Evaluation of a Dynamic Multimedia Instructional Format for the Aldol Reaction

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Abstract

Organic chemistry by many students is seen as a particularly demanding field in their chemistry studies. Research has shown that students find it difficult to obtain information about the chemical properties of molecules from their respective structural formulas. [1] With missing this crucial part of information however, the complex processes at the sub-microscopic level demand a large amount of cognitive resources. Students are tempted to fall back on their intuition or proven habits when working with structural formulas which corresponds to an insufficient connection between the symbolic level and the sub-microscopic level. [2]

In this regard dynamic multimedia instruction formats labelled as "learning videos" have attracted attention of chemistry education research. With the aim to find ways to foster learning in organic chemistry, this article presents the design and evaluation of a dynamic multimedia learning environment using the aldol reaction as an example.

Therefore, it will be explained which general design criteria can be derived from the Cognitive Theory of Multimedia Learning and how they can be interpreted for organic chemistry [3]. Considering their respective underlying mode of action, the design criteria are then applied to the example of the aldol reaction. Of particular importance are superordinate guiding principles that systematize chemistry as a natural science and are referred to as "basic concepts" in the German research landscape. [4]

To assess the effectiveness of the instructional material, an evaluation instrument was developed utilizing a post-only design in which the intervention group received the instruction material described above. The control group received the momonedial pendant, which did not differ in content. The sample consisted of 14 undergraduate students who had no prior knowledge of the aldol reaction.

Keywords: *chemistry education, organic chemistry, instructional design, dynamic multimedia, cognitive load, animation mechanism*

1. Introduction

Chemistry's task is it to describe and predict processes on the submicroscopic level. Since it is impossible for the human eye to observe these processes, visualisation has traditionally been of great importance. Through an own scientific notation with a broad catalogue of agreed rules, it is possible for chemists to share information about processes at the atomic level. These notations are called chemical formulae and can convey a great amount of information in a minimum of space. The resulting high density of information is a great challenge, especially for novices and undergraduate students. Empirical findings show that students find it difficult to extract all relevant properties from a given structural formula because of this wealth of information [5]. Organic chemistry therefore is often seen as a particularly demanding field by students.

According to Johnstone, this can be interpreted as an insufficient link between the symbolic and the submicroscopic level, causing students to misjudge reactivity and make incorrect mechanistic predictions [2]. The constant change between both levels requires many cognitive resources that are no longer available in the learning process. The following will describe how dynamic multimedia learning environments can be designed to better match instructional material in organic chemistry to the cognitive premises of undergraduate students. For this purpose, models of cognitive psychology are used which are then dovetailed with fundamentals of chemistry education research.

2. Theoretical framework

In order to model learning in multimedia learning environments, special learning theories have been developed in cognitive psychology. The most prominent one being Mayer's Cognitive Theory of Multimedia Learning (CTML), which can be seen as a further development of Sweller's Cognitive Load Theory [3][6]. It describes learning as taking in and processing information that is then used to construct a mental model. Mental models can then be used to solve various problems. Each step in the construction of the mental model requires cognitive resources. The more abstract and information-rich the learning content is, the higher the resources required. If no more cognitive resources are available, the so-called cognitive overload immediately shuts down the learning process. Consequently, all design principles to be derived from the CTML aim at reducing the cognitive load.

Information processing is carried out in the two autonomously working subsystems within the working memory (Fig. 1). These two channels can simplistically be assumed as a speech channel and a picture channel which process the respective information. Dynamic multimedia, in contrast to static monomedia, offer the possibility to split up information for the two channels and thus protect the working memory from a possible cognitive overload [7]. However, such formats have not yet been able to establish themselves in chemistry studies. Instead, students often resort to classic textbooks, which, from the CTML's point of view, have a higher chance of overloading them cognitively.

When learning with textbooks, the picture channel is used almost exclusively, while the speech channel remains almost unutilised. In addition to an increased risk of cognitive overload, this is also detrimental to the exchange of information between the channels, as the speech channel holds much less information than the picture channel. As a result, students construct an inferior verbal model, which in turn results in a deficient mental model. This provides a possible explanation for the fact that students can often reproduce the surficial features of a molecule at the symbolic level but are rarely able to infer substance properties and reactivity from these structural features [8]. In contrast, when students learn with dynamic multimedia, both channels can be utilised equally to construct two equivalent models in the respective channels. This ultimately results in the construction of a more elaborate and powerful mental model. The reason for this is also the improved exchange of information between the two channels.

Another advantage of learning with dynamic multimedia in chemistry lies in the possibility to depict particle movements. Students do not have to spend any, or at least fewer, cognitive resources to perform these movements mentally and are thus relieved. The resources saved can then be used elsewhere in the learning process, which in turn should result in a more efficient mental model [9][3].

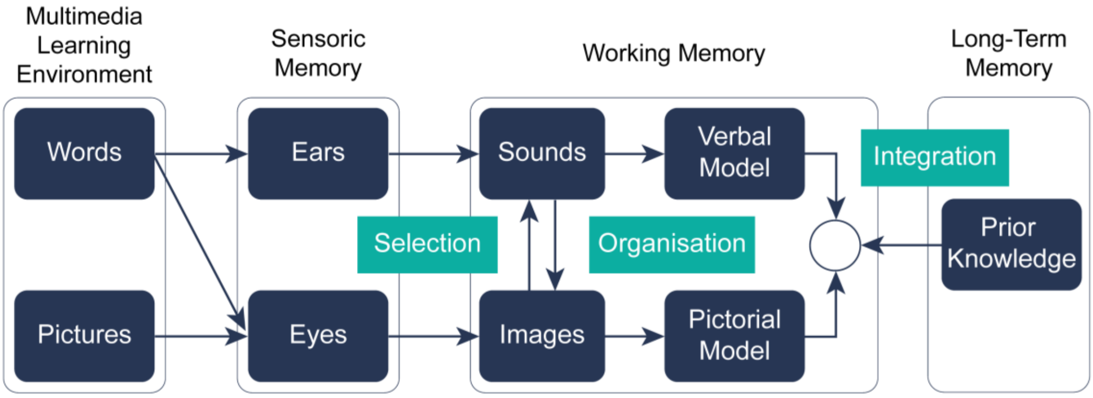

Fig. 1: *Cognitive Theory of Multimedia Learning [3]*

3. Design

Although criteria for the design of dynamic multimedia can already be derived from the CTML, the basic structure of the learning unit for the aldol reaction should first be explained. For this purpose, the Four-Component Instructional Design Model by Merrienboer and Kester (4C/ID model) provides a possible structuring that can be well aligned with the framework of the study and the learning content of the aldol reaction [10]. The 4C/ID model first requires a segmentation of the learning content. The aim is to create sections that can stand on their own without raising major contradictions. Complex reaction mechanisms in organic chemistry are usually quite suitable for this, as the reactivity of a substance can be explained with the structural features at first. The mechanism is then further dissected to produce small sequences, each of which provides a stable intermediate.

The aldol reaction was deliberately chosen as a learning content because it can be divided particularly good into coherent segments and therefore perfectly fits the 4C/ID framework. The alpha-carbon atom as a potential nucleophilic reactive centre can be seen as the starting point of the mechanism. The reaction can then be divided into the aldol addition and aldol condensation since both partial reactions yield stable intermediate products [11]. To frame this tripartite division, two further segments were created: First, an aldol reaction of acetophenone was shown on a macroscopic level in a problem outline. At this point, the students were not able to explain the precipitation of a white solid. That way a cognitive conflict could be induced. Finally, the central aspects of the aldol reaction were summarised in the output. The final segmentation can be seen in Fig. 2.

Fig. 2: *Segmentation according to the 4C/ID model [10]*

The individual segments of the learning unit were again divided into 4 components following the 4C/ID model. The backbone of each segment was the learning tasks, which are shown in Fig. 3 as large spheres in the dashed rectangles. The learning tasks within a segment increase in difficulty and the given assistance from the instructional material is successively reduced represented by the different filling level of the circles. Before solving the tasks, students were provided with supporting information which can be seen as theory knowledge necessary to solve the problems in the given segment. While working on the tasks, students also received procedural information, which can be considered as algorithmic knowledge for solving a specific task. Finally, they got the opportunity to automate their solution paths in part-task practice [10]

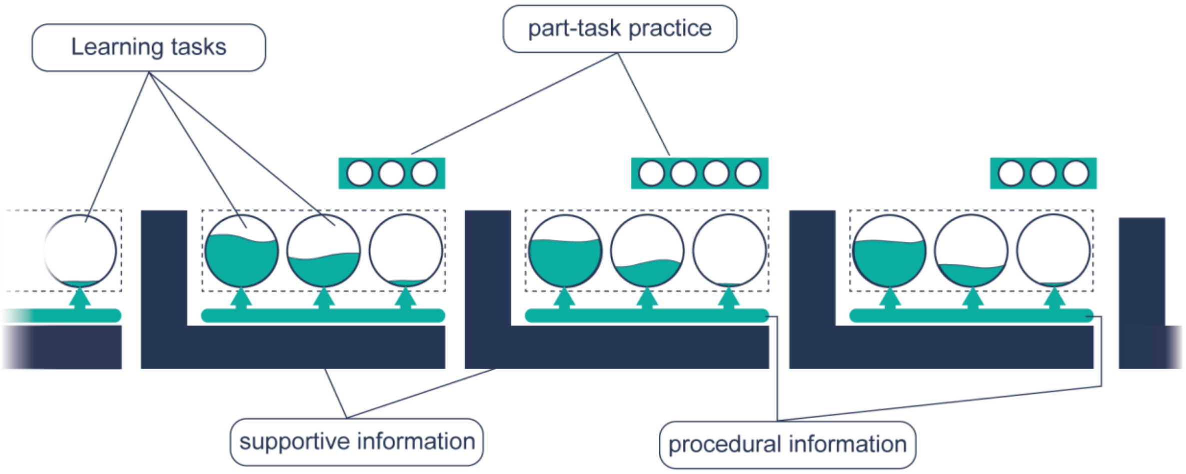

Fig. 3: *Structure of the instructional material according to the 4C/ID model [10]*

Based on the segmentation according to the 4C/ID model, further design criteria for dynamic multimedia learning environments can be derived from the CTML. Since these are necessarily very general, they have to be concretized by findings from chemistry education research. However, an immediate derivation from the CTML is the equal weighting of the speech portion and the image portion in the instructional material. This ensures that both channels are used equally, allowing verbal model and pictorial model to be constructed to the same quality with minimal risk of cognitive overload.

In order to save cognitive resources when connecting relevant information form the instructional material, CTML requires the smallest possible distance between information that needs to be interpreted together [12]. For chemistry, this primarily places demands on the structural formulae presented as well as their labels. Therefore, the ACS style was used for drawing, which is characterised by short bonds within the formulae. Similarly, all relevant labels were placed as close as possible to the corresponding formulae. When displaying mechanisms, the molecules of successive reaction steps were also displayed as close to each other as possible to facilitate the connection of information. This so-called contiguity principle, however, extends not only to the spatial dimension but also to the temporal dimension. So, during post-production, the image and sound tracks were cut in such a way that the acoustic information is presented at the same time as visual information.

To further assist the connection of relevant information the instructional material should contain Cues which indicate togetherness. This can be done in many ways, with the most prominent ones being colours or the use of shapes to draw students' attention. The latter, in the form of the electron pushing formalism (EPF), has always been used in chemistry [13]. In order to concretise this so-called cueing principle, basic or key concepts can be used [14]. These constructs, which are widespread in the German research landscape, represent overarching categories of order that systematise chemistry as a science [4]. For the instructional material, the key concept "thinking in pairs of opposites" was chosen, since the mechanism of the aldol reaction follows the formalism nucleophile/electrophile practically without exception. Thus, with the help of colours, the electron density within the reactants was displayed and the molecules were then colour-coded as nucleophile or electrophile.

To support students in their selection of information, the so-called redundancy principle requires to omit all information that is not strictly necessary. Besides decorative elements, parts of the structural formulae which were not necessary for the respective reaction step were temporarily blurred out. This way, attention could be focused solely on the relevant reactive centres. For duplicate information, which in a narrower sense also represent redundant information, the redundancy principle applies only to a limited extent - "repetition is not redundancy" [15].

Strict adherence to CTML and 4C/ID model results in a very "sterile" product. Since this can also have a negative impact on learning, minor design decisions such as using bézier curves for animations or adding smooth crossfade transitions were made in favour of the highest possible perceptual fluency [16].

4. Evaluation

The instructional material was evaluated in a post-only design in which the intervention group received the instructional material described above. The control group received the momonedial pendant as a treatment, which did not differ in content.

All students (*N* = 14) were randomly assigned to one of the two groups and received the respective treatment over the course of 2 hours. Afterwards, the students were asked to fill out a questionnaire in which they were to evaluate their respective material. They were also asked how they felt during the treatment. A four-level ordinal Likert scale was used for this purpose, on which students could indicate their agreement or disagreement. Finally, a post-test was conducted to measure the transfer ability of the two groups. However, due to COVID-restrictions in place, the original sample size was reduced in such a way that the post-test did not provide useful data. Therefore, selected findings from the questionnaire part of the evaluation are presented below.

Both groups stated that they felt they had learned something about the aldol reaction after the treatment. Furthermore, they stated that they enjoyed the treatments and that they felt motivated during learning. Both groups would also use further material on other reaction mechanisms.

The use of colours in the material was considered very useful by both groups, especially for the colouring of electrophile and nucleophile. However, differences in the perception of the mechanism were evident. For example, the control group reported getting confused with nucleophile and electrophile more often than the intervention group. When asked whether they could comprehend the movements of the electron pairs within the mechanism the intervention group answered with "Strongly Agree", while the control group answered with "Agree". These findings were consistent with another item which asked if the students found it hard to follow the mechanism in general. Again, the control group stated that it was more difficult for them.

The control group also reported that they had to pause their work on the material more often and had to re-read sections more often. Interestingly, the control group stated that they found it easier to connect relevant information within the material.

5. Outlook

The evaluation showed that the 4C/ID model is an eligible theoretical framework for planning multimedia learning environments in organic chemistry. For construction, the CTML can be used, whose design criteria are ideally concretised with findings of chemistry education research. For the aldol reaction, the key concept "thinking in pairs of opposites" can be used to colour-code molecules as nucleophile or electrophile.

The evaluation was often, but not always, in favour of the dynamic multimedia material. Although the students in the intervention group stated that they were able to follow the mechanism better overall, the static monomedia material was rated better in terms of handling. The reason for this could be that textbooks or lecture notes are still the most frequently used materials for learning chemistry and their use is therefore more familiar to the students.The aim of a next study should be to investigate these findings quantitatively with a large sample size.

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