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Difficulties encountered by African students' learning the semiotic representations of the spatial structure of organic molecules

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Abstract

This study aims at identifying and analysing the learning difficulties of beginners regarding the semiotic representations of the spatial structure of organic molecules from a visualization perspective. The three-dimensional arrangements of atoms in molecules are depicted by two-dimensional drawings such as Cram representations or Newman projections which constitute two different semiotic systems. Treatment and conversion of semiotic representations need visuospatial abilities such as mental rotation or iconic visualization. A questionnaire was designed to determine to what extent grade 12 students in Benin (Africa) master the transformations of the semiotic representations of organic molecules. A paper-and-pencil test including four questions was administered to 340 students. The analysis of the answers revealed that a great proportion of students do not master the treatments of the Cram's semiotic representations. Most students responded randomly to say whether one or two permutations between atoms of a chiral molecule lead to the same molecule or its mirror image. No student could draw a correct staggered conformation from an eclipsed conformation which shows that the students do not master mental rotation. One third could not identify conformational isomers out of a list of six conformations because the iconic visualization is not operative. Moreover most of those who identified conformational isomers have a limited understanding of that concept. The most difficult task seems to be the conversion of a Cram representation to a Newman projection. The analysis of numerous incorrect answers leads to the assumption that spatial orientation is ineffective in most students.

Keywords: Semiotic representations, learning difficulties, visualization, spatial abilities, organic molecules

Context

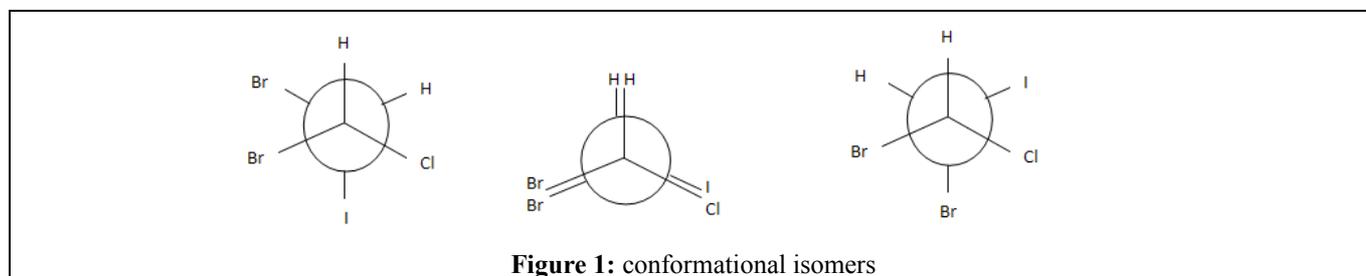
This study takes place in Benin which is a small and poor country in west Africa. Students are numerous even in upper secondary schools, about 50 or 60 per class. There are no computers, only a few ball-and-stick models. The teachers use photocopies of the reference textbook which is a French one edited in 1991 before the syllabus was designed.

Framework of the study

Molecules are imperceptible entities; however chemists have a lot of signs and symbols to depict them and specially their spatial structure. This study aims at identifying and analysing the learning difficulties of beginners regarding the semiotic representations of the spatial structure of organic molecules from a visualization perspective. The three-dimensional arrangements of atoms in molecules are depicted by two-dimensional drawings such as Cram representations (solid wedged and hashed wedged bonds) or Newman projections. Each type of representation constitutes a semiotic system [4]. Knowing the rules, conventions and symbols of each type of representation allows understanding the meaning of a representation. These representations may undergo two types of transformations: a treatment within the semiotic system -for example a rotation about a C-C axis in a Cram representation leads to another Cram representation- and a conversion from one system to another one. Conversions are transformations of representations that consist in changing the semiotic system without changing the object being depicted-

for example a conversion of a Cram representation to a Newman projection or vice versa.

The way of interpreting or using the semiotic representations of molecules depends on the task to be done. It could be done with a diagrammatic reasoning [9] which means applying a rule or using an analytical reasoning from diagrams without invoking mental images. An iconic visualization [3] can also be used which is the merging of two cognitive operations probably involving mental images. The first operation is a discriminative recognition of shapes and the second operation is the identification of the objects corresponding to the identified shapes.



On figure 1, you can see at first glance that the Newman projection in the centre is eclipsed and the two others are staggered. The two staggered Newman projections are conformational isomers because the atoms attached to the back carbon are not in the same place. But each staggered Newman projection and the eclipsed Newman projection are also conformational isomers because the bonds are not in the same place and the atoms are the same. This example shows that when the two operations are merged, the recognition of spatial structures is easy. The last way of interpreting the semiotic representations of molecules rests on mental visualization also called visual imagery or mental imagery [5, 6, 7] which involves mental rotations and other spatial abilities. Many scholars showed that visuospatial abilities are hard to acquire [1, 2, 6, 8, 10, 11] and that teachers are not always aware of that.

Goal of the study

In Benin, there is a national syllabus taught in French. The knowledge to be taught in the last year of the upper secondary school (grade 12) includes the spatial structure of molecules (Cram representation), the conformational isomers of cyclohexane and ethane, enantiomers (with one C*) and optic activity. This is an introductory course in organic chemistry preceding the courses which will deal with the reactivity of organic compounds. The Newman projections are not explicitly mentioned in the syllabus but they are presented in the reference textbook and are widely used by the teachers.

Our research questions from a visualization point of view are the following:

To what extent do grade 12 students in Benin master the semiotic representations of organic molecules?

- Do they master the rules within the Cram semiotic system?
- Are they able to convert a Cram representation into a Newman projection?

We designed a paper and pencil questionnaire made of four questions. It was administered to 340 students aged 17 to 20, after they had been taught the points above.

Overview of the questionnaire

The first question deals with the permutation of atoms in a chiral molecule. A permutation is clearly a treatment transformation within the Cram semiotic system. The students had to say whether they agree or do not with the statements that were proposed. Does the permutation of two atoms linked to the carbon produce the same molecule or its mirror image? Does a double permutation produce the same molecule or its mirror image? The purpose of this question was to determine whether the students know the double permutation rule which is often used by the teachers to recognize pairs of enantiomers. We expected two types of reasoning, namely applying a rule or using mental visualization.

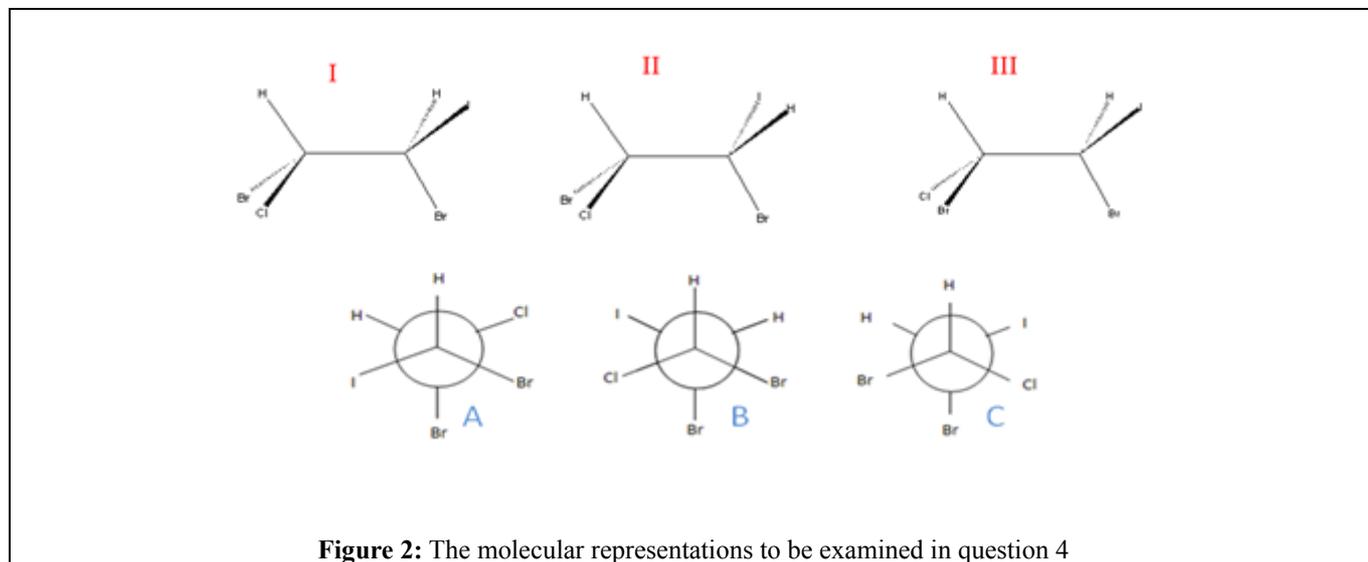
In the second question the students were asked to draw a Cram representation after rotating a group of atoms about the C-C axis of an eclipsed Cram representation. A rotation of 60 degrees was required and an arrow showed the direction of rotation. The result of this treatment transformation within the Cram se-

miotic system is a staggered conformation and should be obtained with a mental rotation.

In the third question the students had to say which representations out of a list of six Cram representations – three staggered, three eclipsed – were conformational isomers. Two groups of representations were constituted of conformational isomers, the first one included an eclipsed representation and a staggered one, the second one two of each type. We expected two types of reasoning, namely iconic visualization or mental visualization with several steps which are treatment transformations. We also expected that some students would rely on the global shape of the representation to answer and would not pay attention to the position of the different atoms.

In the last question the students were confronted by three Cram representations and three Newman projections. They had to say whether a Newman projection could or could not be obtained by looking mentally on the left or on the right of a Cram representation. For example (figure 2) if one looks at III Cram representation from the left, none of the Newman projection fits, and from the right the correct one is A. This is a complex task typically a conversion between two types of representation requiring mental visualization including spatial orientation and rotation about a vertical axis for instance.

The analysis of the answers was based upon the framework and some categories of answers stemmed from the data after repeated readings.



Results and discussion

In question 1 the students had to say whether they agreed or not with four statements that were proposed. The results are in table 1 below, the correct choices are labelled with a star. A majority of students made a correct choice when one permutation was involved. This was no longer so for two permutations. It is more profitable to examine the consistency of the choices made by the students. 43% of the students surveyed made coherent and correct choices for the first two statements, 27% for the last two statements and only 9% made four correct choices. Most students responded randomly. So we can presume that the rule is not known or memorised and there is no efficient visualization.

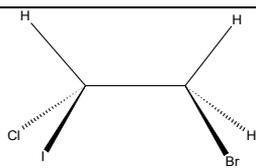
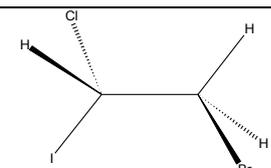
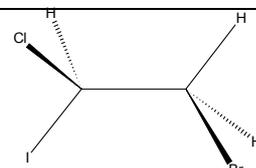
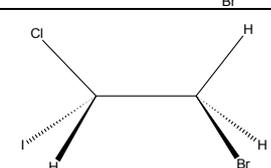
Table 1: distribution of answers to question 1 (* correct choices)

	statements	Agree (N=340)	Do not agree	No answer
S1	One permutation of two atoms gives the mirror image of the molecule	63%*	35%	2%
S2	One permutation of two atoms gives the same molecule	36%	61%*	2%
S3	Two permutations of two atoms give the same molecule	46%*	51%	2%
S4	Two permutations of two atoms give the mirror image of the molecule	53%	44%*	3%

To answer question 2 the students should make a mental rotation of 60 degrees of a group of atoms about the C-C axis. No student drew a correct staggered conformation. One out of ten (10%) provided a staggered conformation but did not consider the positions of the atoms (6%, see table 2) or the alternation of the lines (4%) representing the bonds [8]. Two thirds of the students surveyed (69%) drew an eclipsed conformation and a majority (56%) placed the atoms as if they had permuted them without rotating the bonds (table 2). Other students (21%) made various errors such as no respect of the angles, of the symbolism, of the alternation of the bonds. It is quite clear that there is no efficient mental rotation for a majority of students. Moreover we wonder whether they know the value of the angles and what their ability to imagine a rotation about the axis can be.

In question 3 the students had to find the conformational isomers out of six Cram representations. Half the students surveyed (50%) proposed conformational isomers but 39% considered that conformational isomers are pairs of different kinds, staggered and eclipsed conformations and 2% of a same kind eclipsed - eclipsed or staggered - staggered conformations. Thus we consider that 41% of the students had a limited understanding of the conformational isomerism. 9% of the students proposed any kind of conformational isomers (eclipsed - staggered and eclipsed - eclipsed or staggered - staggered conformations) and thus had a sound understanding. Nearly a third (34%) produced a line of reasoning based on the shape of the conformational isomers without taking the atoms into account. In those cases the iconic visualization is not operative because the discriminative recognition of shapes is favoured and the identification of the object corresponding to the identified shapes is overlooked. 16% did not answer at all.

Table 2: some answers to question 2

initial eclipsed conformation		expected staggered conformation	
staggered conformation with incorrect positions for the atoms (6%)		eclipsed conformation (56%)	

In question 4 the students should assign a Newman projection to a Cram representation if possible. This task involving the conversion of a Cram representation to a Newman projection seems to have been the most difficult one. No student gave a totally correct answer. More than a third (36%) did not answer at all. Nearly half the students did not answer each question. 27% of the students made a choice which means that they inverted the symbol of the front carbon and that of the back carbon (the circle and the dot). Nearly a quarter of the students surveyed (24%) seemed to look at a Cram representation from both sides. For example they associated the III Cram representation with the B Newman projection. This choice leads to presume that they firstly looked at the front carbon from the left as expected but then the back carbon seems to have been seen from the right. We assume that most students cannot manipulate proper mental images or even generate them.

Concluding remarks

A great proportion of students do not master the treatments of the Cram's semiotic representations or the conversion to Newman projections. Indeed the permutation rule is not known, the mental rotation is not efficient and the students find it difficult to visualize the positions of atoms after rotation [10], the iconic visualization is not operative for all of them. Some reasons of a different nature may be proposed: there are not enough visual aids in the learning environment, not enough importance is given to the symbols and the angles of the spatial structures, and teaching conformational isomers mainly or only with ethane

does not help. Further research is needed to find out more reasons. Therefore we are now conducting in-depth interviews to uncover the students' lines of reasoning.

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