Research Article

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How do students apply the octet rule and how do they justify this application?

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Abstract: In this paper we describe an intervention study on the application of the octet rule. This study was conducted at a German University with students in their first- and second undergraduate year. As repeatedly observed by us before, the evaluation of the study confirmed that the students have difficulties with the application of the octet rule in general, but above all for charged molecules. After an intervention, which consisted of a detailed checklist for the application of the octet rule and training opportunities, the students' competences increased, especially for the tasks which included charged molecules. Students' explanations were not as good as expected; the linguistic quality did not increase significantly from pre-to post-test. This is not surprising, because the training of argumentation skills was not part of the intervention. The intended goal, training the application of the octet rule, has been achieved.

Keywords: first-and second-year students; general chemistry; octet rule; organic chemistry.

Introduction

In Germany, the first encounter with the octet rule often occurs while starting to learn the topic "ions and the ionic bond". More useful is the application of the octet rule if students have to develop Lewis structures or more generally valence bond formulas in Organic Chemistry, because many formulas consist of the elements carbon, oxygen and nitrogen, all elements where the octet rule can be applied as the following quotation from a German school book illustrates: "*in a stable molecule each atom has to be surrounded by four electron pairs, only the H atom has one electron pair*" (Asselborn et al., 2008). Several chemistry books commonly used at university only apply and define the octet rule for valence bond formulas (Ehlert, 2017; Mortimer & Müller, 2003; Schmuck, 2013). The only exception from the rule is then needed for hydrogen because as an element of the s-block, hydrogen strives to the electronic configuration of Helium and therefore to having two electrons in its valence shell. For the development of Lewis structures the students have to consider the octet rule and the number of the main group in the periodic table of elements. The number of the main group gives the information on the number of valence electrons the respective element has at its disposition. The students can then draw valence bond formulas and decide whether a charge is needed or not. In several courses at our university, we observed that students tend do use a charge for their decision, whether the element satisfies the octet rule or not; if there is a charge, the students often decide that the role is not satisfied. Based on this observation, an intervention study on the application of the octet rule for drawing valence bond formulas has been developed, used and evaluated and will be discussed in this paper.

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Theoretical background

Lewis structures were developed and first published by G. N. Lewis (Lewis, 1916). The reason for the use of these structures, namely as a link between structure and property has not changed since then. However, students do not know why they have to learn how to draw Lewis structures (Cooper et al., 2012). This also hinders the meaningful learning of the students (Bretz, 2001; Cooper et al., 2010). The drawing of Lewis structures, which seems to be a simple task from the experts' view, is not only complex for the students, but also often meaningless to many of them (Cooper et al., 2010). The cognitive load of students increases with the structural complexity (Tiettmeyer et al., 2017). Therefore, the students first were introduced to the properties of substances, and three-dimensional structures before they had to construct Lewis structures by themselves (Cooper et al., 2012). However, many students are not able to construct simple Lewis structures. Some students draw Lewis structures intuitively; there is a lack of systematic approach (Karonen et al., 2021).

Overall, over the years many ideas how to support students when they have to draw Lewis structures have been published, as for example: step-by-step procedures that students can follow when they have to construct Lewis structures (Ahmad & Omar, 1992; Ahmad & Zakaria, 2000; Carroll, 1986; Imkampe, 1975; Kildahl, 1991; Lever, 1972; McArdle, 2019; Miburo, 1998; Nassif & Czerwinski, 2015; Pardo, 1989; Packer & Woodgate, 1991), scaffolds – analog (Kiste et al., 2016) or computer based (Cooper et al., 2009), games (Lionetti, 1951; Kavak et al., 2021) or whole conceptual frameworks (Wang & Barrow, 2013).

By combining the method writing-to-learn with Lewis structures, a new approach has been used; the students read and wrote about the original paper of Lewis to ensure conceptual learning (Finkenstaedt-Quinn et al., 2019; Shultz & Gere, 2015). Students' argumentation skills are in recent research often evaluated (Juntunen & Aksela, 2014; Yaman & Hand, 2022). Students often have problems if they have to build argumentations (Deng & Flynn, 2021). Therefore, scaffolds for supporting students' argumentation are also in the focus of recent research (Lieber et al., 2022a; Luo et al., 2020). Although argumentation skills should also be helpful for explaining facts or phenomenons, arguments and explanations are not synonyms (Deng & Flynn, 2021). Arguments justify a fact or phenomenon that is not agreed-upon, whereas explanations focus on the explanation of agreed-upon facts or phenomenons (McNeill et al., 2006; Osborne & Patterson, 2011). Students' justifications in their written answers in this study on the application of the octet rule, should therefore be classified as explanations and not as arguments.

Design of the study

Although the banning of the octet rule for the drawing of Lewis structures has been proposed (Lim, 2018), the rule and its application are commonly known and used both at school and at university. To evaluate which competences for applying the octet rule the students have at the beginning of their university studies, the intervention study included students' explanations for their decision whether the atoms fulfill the octet rule or not. In the study discussed in this paper, the training of the argumentation competences was not intended. All students are from German schools and should therefore know what they are meant to do if the task includes the verb "justify" (for example the application of rules). Such verbs (called in German "*Operatoren*") are used in tasks and in the written exams at school and should therefore be commonly known by the students. These "*Operatoren*" are defined by the "*Kultusministerkonferenz* (kmk)" (conference of ministers responsible for school education) (kmk). Therefore, the intervention has focused only on the application of the octet rule. Because the justifications of the students have only been used for gaining insight in their competences with regard to the octet rule, an own framework for the evaluation of students' answers has been used. Details on the study will be presented and discussed below.

Goal

For this study the following research questions will be evaluated and answered:

(1) How do the students apply the octet rule in the pre-test?

(2) How do the students justify their choice for deciding whether the octet rule is satisfied or not?
(3) How are the differences in the students' answers after the intervention?

Sample

Although especially pre-service chemistry teachers are of interest in our research, we also integrated other first-year students in our study to ensure a sufficient number of participants. Pre-service chemistry teachers should know how to apply the octet rule, because, as stated above, this rule is commonly used at school. Overall, 148 students participated in the pre-test. Only if the students completed the survey they were included in the study; for the pre-test, 96 students completed the survey. Only 20 students participated in both pre- and post-test. Table 1 gives an overview on the sample of this study.

Design of the tasks (including the intervention)

For the intervention study, an identical questionnaire for the pre-and post-test has been developed; for four different structural formulas the students had to answer a question with yes or no and then to justify their choice (see Table 2; for the questionnaire see Supplementary Material).

For the design of the tasks, two main points were taken into account:

- The formulas and the elements that are part of the formulas should be most certainly familiar for the students, because from previous studies it is known that most students that are studying chemistry or another STEM subject had chemistry lessons during their schooldays (Hermanns & Schmidt, 2019).
- The molecules should be quite small, because it is known that students often struggle with chemical formulas (Taskin & Bernholt, 2014). By choosing small molecules, the students can focus on the relevant information. It also reduces the cognitive load of the task at hand (Kayler, 2014; Sweller, 1988; Tiettmeyer et al., 2017).

The intervention consisted of a step-by-step procedure for applying the octet rule. Step-by-step procedures are quite common for this sort of application; several examples can be found in the literature (Ahmad & Omar, 1992; Ahmad & Zakaria, 2000; Carroll, 1986; Miburo, 1998; Packer & Woodgate, 1991). All known step-by-step procedures are very complex and therefore in our view not very user friendly. Therefore, for this study, a new step-by-step procedure has been developed (see Supplementary Materials). This step-by-step procedure combines the periodic table of elements with the application of the octet rule which was also not done in the other step-by-step procedures. By doing so it is made transparent to the students that they can find relevant information for the application of the octet rule in the periodic table. The first version of the tasks and the step-by-step procedure had been tested with students studying life or nutritional sciences; 16 students participated. They worked by themselves and could only use the step-by-step procedure, no other support was allowed. In the questionnaire the students were asked what part of the procedure was supportive or not and why. In an open item they could write

Table 1: Sample.

Study subject	Course	First- or second undergraduate year	Pre-test (*N* = 96)	Pre- and post-test (*N* = 20)
Pre-service chemistry teachers	Inorganic and general chemistry (group 1)	First undergraduate year	*N* = 51 (53.1%)	*N* = 3 (15.0%)
Pre-service chemistry teachers	Organic chemistry (group 2)	Second undergraduate year	*N* = 22 (22.9%)	*N* = 10 (50.0%)
Geological sciences	Inorganic and general chemistry (group 3)	First undergraduate year	*N* = 19 (19.8%)	*N* = 7 (35.0%)
Pre-service biology teachers	Inorganic and general chemistry (group 4)	First undergraduate year	*N* = 4 (4.2%)	–

Table 2: The tasks for the intervention study.

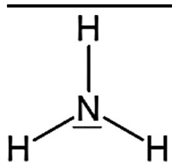
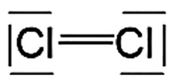
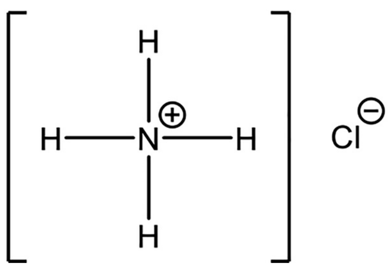
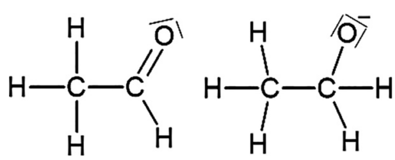
Structural formula	Task
	Is the octet rule satisfied for the nitrogen atom (*N*)? Yes/no Justify (2–3 sentences)
	Is the following statement correct?: "The chlorine atoms (CL) satisfy the octet rule?" Yes/no Justify (2–3 sentences)
	Is the octet rule satisfied for the nitrogen atom (*N*)? Yes/no Justify (2–3 sentences)
	Is the following statement correct?: "The right oxygen atom (O) does not satisfy the octet rule?" Yes/no Justify (2–3 sentences)

Table 3: The intervention for the application of the octet rule.

Slide	Content
1	Octet rule First three steps of the procedure Periodic table of elements Example: valence bond formula of N_2O
2	Last four steps of the procedure (including checking whether the molecule is charged or not) Solution for the example: valence bond formula of N_2O
3	Task: write down the valence bond formulas for N_2, CH_4, PH_4Br, $CH_3–CH_2–COO^-$
4	Solution to the task: valence bond formulas for N_2, CH_4, PH_4Br, $CH_3–CH_2–COO^-$

down what they wanted to contribute. Because the students felt supported by the step-by-step procedure and no concrete information on the improvement of the material was given, the step-by-step procedure remained the same for the study.

The intervention consists of three steps: the step-by-step procedure for the application of the octet rule, tasks for practicing the application and the solutions to these tasks (in total four power point slides). An overview on the intervention is shown in Table 3 (for the complete intervention material see Supplementary Material).

The use of the tasks and the intervention

The intervention was conducted in those courses where the teachers of the course agreed to participate; in total four teachers participated; each course had another teacher (one professor, three post-docs). The teachers used the intervention instead of their own teaching materials for the octet rule; the topic “octet rule” was part of the content in their courses. This ensured that no course time would be used only for the study. The students were informed on the use of the data and agreed with the evaluation of those data. Ethical guidelines have been followed. The slides used for the intervention were made available to the students using the Moodle platform that was used in the courses.

In the pre-test, the students received during the course the questionnaire with the four tasks (see Table 2 and Supplementary Material) as online questionnaire. The students had approx. 7 min. for completing the questionnaire. In the intervention, the course leaders used four power-point-slides for teaching and explaining the step-by-step procedure. The solutions of the tasks in the pre-test have not been discussed. After the explanation (first two slides) the students solved the tasks of the intervention by themselves (third slide). The solution was then presented and discussed with all (fourth slide). The students then received the questionnaire as post-test, again as an online questionnaire. The students had again approx. 7 min. for completing it.

The coding process

The tasks include the application of the octet rule to choose whether the question should be answered with “yes” or “no” and the students’ written justification for this choice. Therefore, two rounds of coding were needed for evaluating the study. The method of qualitative content analysis (Kuckartz, 2016) has been used for the coding. Approximately 20% of each round has been coded also by the corresponding author. The first round of coding evaluated only whether the students’ explanations were technical correct or not. Both coders discussed and compared their assignments until 100% inter rater agreement was reached (Saldaña, 2013). The second round of coding took also into account the linguistic quality of the justifications. The coding consisted of the marking of students’ written explanations with points and has been done comparable to marking students’ explanations at school. For a task on justification, the marking would focus on both the linguistic quality and the technical correctness of the answer; only students who wrote a correct justification would receive full points. The coding scheme for this study has been developed by us, supported by a linguist. The inter coder reliability after Brennan and Prediger (1981) was sufficient ($\kappa = 0.86$). Tables 4 and 5 give an overview over both rounds of coding with examples from the students’ justifications (translated from German to English).

For evaluating and discussing the assessment of both rounds of coding, the statistical software SPSS has been used.

Table 4: The first round of coding (technical correctness of the content).

Action	Example from the pre-test (task 1)
Dividing the justification in sections	The nitrogen atom has five free electrons at its disposition./Two of these electrons stay without bonding – the other three electrons bond with one electron respectively of the hydrogen atom./Because nitrogen has a higher electronegativity it claims more electrons for itself and has so a full shell.
Coding of these sections: Wrong (–) partially correct (~) correct (+)	The nitrogen atom has five free electrons at its disposition (~)/Two of these electrons stay without bonding – the other three electrons bond with one electron respectively of the hydrogen atom (+)/. Because nitrogen has a higher electronegativity it claims more electrons for itself and has so a full shell (–).
Assessment of the whole justification: 0 points (only–or ~) 1 point (only ~ or +/~ or ±) 2 points (only +)	1 point, because 1 × (~), 1 × (–) and 1 × (+)

Table 5: The second round of coding (quality of the justifications).

Code (points)	Example from students' justifications
No justification (0)	The nitrogen atom has here only seven electrons (pre-test; task 3).
Justification contains words as "because", "as", "therefore" or "which is why" (1)	The chlorine atom has too many electrons. The electrons of the bonds count for both atoms. Because of this each chlorine atom would have 10 valence electrons (pre-test; task 2).
Justification fits the answer, but is not complete (2)	The octet rule says that many molecules create bonds where they have eight valence electrons, therefore a full valence shell. Nitrogen itself has five valence electrons. Each hydrogen atom contributes one electron (pre-test; task 1).
Complete and correct justification (3)	The statement is not correct, because the right oxygen atom possesses three free electron pairs and together with the bond to the carbon atom accordingly has eight electrons in total. That means that the octet rule is satisfied (pre-test; task 4).

Results and discussion

For discussing and answering the research questions, the data were evaluated taking into account two possible settings: on the one hand, without taking into account whether the students answered the questions correctly or not, and on the other hand, taking into account whether the students answered the questions correctly or not (if the answers were not correct or the students did not give an answer, the students received zero points). For the following four groups, both settings have been calculated using SPSS:

- Pre-test of all students.
- Pre-test of the four groups of students separately.
- Pre-test of those students who completed the post-test.
- Post-test of all students who completed the post-test.

Research question 1: how do the students apply the octet rule in the pre-test?

For answering the research question for all tasks, the arithmetic means and standard deviations for the technical correctness of students' justifications have been calculated; an overview gives Table 6.

When comparing the results for the four tasks for all students, it is noticeable that the arithmetic mean for the technical correctness of task 1 is the highest (M = 1.12 or 0.97) with a standard deviation of 0.945. The arithmetic mean is the highest regardless of whether the students answered the question correctly or not. For both cases, the students' answers differ quite widely. Although it can be assumed that the students know the valence bond formula of NH_3 by sight, not all are competent in explaining the correctness of this formula.

Table 6: Arithmetic means and standard deviations for all tasks and groups (pre-test).

Group	Task 1	Task 2	Task 3	Task 4
All (N = 96)	1.12 (0.921)	0.74 (0.897)	0.91 (0.952)	0.71 (0.928)
	0.97 (0.945)	**0.67 (0.914)**	**0.67 (0.925)**	**0.51 (0.846)**
Group 1 (N = 51)	1.12 (0.973)	0.59 (0.853)	0.82 (0.953)	0.71 (0.965)
	1.02 (0.990)	**0.51 (0.857)**	**0.57 (0.900)**	**0.43 (0.831)**
Group 2 (N = 22)	1.55 (0.739)	1.41 (0.854)	1.23 (0.922)	1.32 (0.839)
	1.45 (0.800)	**1.36 (0.902)**	**1.09 (0.971)**	**1.09 (0.921)**
Group 3 (N = 19)	0.74 (0.806)	0.42 (0.769)	0.79 (0.976)	0.16 (0.501)
	0.37 (0.597)	**0.37 (0.761)**	**0.42 (0.838)**	**0.16 (0.501)**
Group 4 (N = 4)	0.74 (0.957)	0.50 (0.577)	0.75 (0.957)	0.00 (0.000)
	0.50 (1.000)	**0.25 (0.500)**	**0.75 (0.957)**	**0.00 (0.000)**

In bold: taking into account whether the students choose "yes" or "no" correctly.

Table 7: Results of the Mann-Whitney test for comparing both groups of pre-service chemistry teachers.

Group	Task 1	Task 2	Task 3	Task 4
Group 1 (*N* = 51) first year	1.12 (0.973)	0.59 (0.853)	0.82 (0.953)	0.71 (0.965)
	1.02 (0.990)	**0.51 (0.857)**	**0.57 (0.900)**	**0.43 (0.831)**
Group 2 (*N* = 22) second year	1.55 (0.739)	1.41 (0.854)	1.23 (0.922)	1.32 (0.839)
	1.45 (0.800)	**1.36 (0.902)**	**1.09 (0.971)**	**1.09 (0.921)**
Significance	*p* = 0.093	*p* = 0.001	*p* = 0.095	*p* = 0.010
	***p* = 0.088**	***p* = 0.000**	***p* = 0.026**	***p* = 0.002**
Effect size	*d* = 0.472	*d* = 0.961	*d* = 0.434	*d* = 0.656
	***d* = 0.459**	***d* = 0.976**	***d* = 0.564**	***d* = 0.769**

In bold: taking into account taking whether the students choose "yes" or "no" correctly.

Because the arithmetic means for all groups differ and the standard deviations are quite high, a Mann-Whitney test has been calculated to explore whether the differences in the rating are statistically significant or not. First, both groups of the pre-service chemistry teachers (first year vs. second year undergraduate students) have been compared. For all data, see Table 7.

The results for all tasks are statistically significant (effect sizes between *d* = 0.459 and 0.976); the technical correctness of the answers to the tasks from the second year students is overall more correct than the technical correctness of the answers from the first year students. Although the octet rule is part of the school curriculum, the application for Lewis formulas seems not to be common for the first year students. Because the results of the second year students are significantly better, it can be assumed that the students learn the application at University, although especially the arithmetic means for tasks 3 and 4 show that the second year students also are not very secure in applying the rule for charged molecules. When taking into account whether the students answered the questions correctly, the data are even more statistically significant.

Second, the first year pre-service chemistry teachers (major chemistry students) are compared with both groups of students, who are not studying chemistry as major students (minor chemistry students). The differences between those groups are statistically not or only somewhat significant (see Table 8). However, the data for task 4 are the most significant of these data. In particular, negatively charged molecules seem to be problematic for students who are not studying chemistry as their major subject. Two reasons can be assumed: the students did not enroll in chemistry courses during their school days or their motivation for technical content in chemistry is less distinctive than for the major students, who are pre-service chemistry teachers.

Not only the students can be allocated in two groups, this is also of interest for the tasks. Task 1 and 2 include molecules without charge; in task 3 and 4 both molecules are charged (one positively and one negatively). Therefore, a Mann-Whitney-test has been calculated to evaluate whether the differences of the results between both groups of tasks (without or with charge) are statistically significant. Table 9 gives the arithmetic means (*M*), standard deviations (SD), significance (*p*) and effect size (*d*) for the technical correctness of all tasks (ratings of the tasks have been added; scale therefore between 0 and 4).

Table 8: Results of the Mann-Whitney test for comparing major and minor students (all first year).

Group	Task 1	Task 2	Task 3	Task 4
Major (group 1) (*N* = 51)	1.12 (0.973)	0.59 (0.853)	0.82 (0.953)	0.71 (0.965)
	1.02 (0.990)	**0.51 (0.857)**	**0.57 (0.900)**	**0.43 (0.831)**
Minor (groups 2 and 3) (*N* = 23)	0.74 (0.810)	0.43 (0.728)	0.78 (0.951)	0.13 (0.458)
	0.39 (0.656)	**0.35 (0.714)**	**0.48 (0.846)**	**0.13 (0.458)**
Significance	*p* = 0.108	*p* = 0.543	*p* = 0.165	*p* = 0.012
	***p* = 0.012**	***p* = 0.515**	***p* = 0.357**	***p* = 0.152**
Effect size		–	–	*d* = 0.688
	***d* = 0.699**	**–**	**–**	**–**

In bold: taking into account taking whether the students choose "yes" or "no" correctly.

Table 9: Statistical data for both groups of tasks (pre-test; N = 96).

With or without regard to answering correctly	Without charge (tasks 1 and 2)	With charge (tasks 3 and 4)	Significance effect size
Without	M = 1.86 sd = 1.567	M = 1.61 sd = 1.552	
With	M = 1.66 sd = 1.595	M = 1.16 sd = 1.496	p = 0.023 d = 0.323

For both cases (without and with answering correctly), the arithmetic means for the tasks without charge are higher than with charge. Statistically significant is this difference for the case "with answering correctly". Both fits with our observation that the students have especially difficulties with charged valence bond formulas. Although they know in principle how to apply the octet rule, the charge is unsettling them. Significantly less students decide correctly if there is a charge. For teachers this means that they should include charged examples when the students are learning how to apply the octet rule and explicitly discuss why atoms are positively or negatively charged. Therefore, the intervention included an example of a charged molecule. Reasons for the problems the students have with applying the octet rule to charged molecules can be found in their answers as the following quotes illustrate (all for task 4): "*the octet rule is not satisfied for the right oxygen atom, because if you add all bonding and not-bonding electrons, the total sum would be nine*" and "*one electron too much*" (comment: the negative charge was interpreted as an electron) or "*the octet rule is satisfied, but the bonding is unlikely, because the molecule has a negative charge*". Some students are insecure if the molecule is charged. Therefore, the intervention discusses this explicitly.

Because the students have to apply the octet rule for all tasks, correlations between all tasks have been calculated. As can be expected, between all tasks significant correlations can be observed ($r_S = 0.312^{**}$–0.491^{**} without regard to answering correctly; $r_S = 0.280^{**}$–0.525^{**} with regard to answering correctly).

Summarizing, our observations that students have difficulties with the application of the octet rule, especially for charged molecules, have been confirmed by evaluating the results of the pre-test.

Research question 2: how do the students justify their choice for deciding whether the octet rule is satisfied or not?

Because students should know from their school days what to do if they should justify their choice in a task, the linguistic quality of students' answers has also been evaluated. For answering the research question, for all tasks the arithmetic means and standard deviations for the linguistic quality of students' justifications have been calculated; an overview gives Table 10.

Table 10: Arithmetic means and standard deviations for all tasks and groups (pre-test).

Group	Task 1	Task 2	Task 3	Task 4
All (N = 96)	0.68 (0.877)	0.65 (0.794)	0.40 (0.657)	0.42 (0.735)
	0.59 (0.889)	**0.46 (0.807)**	**0.27 (0.624)**	**0.29 (0.710)**
Group 1 (N = 51)	0.49 (0.674)	0.47 (0.612)	0.18 (0.385)	0.18 (0.385)
	0.41 (0.669)	**0.29 (0.576)**	**0.14 (0.348)**	**0.10 (0.300)**
Group 2 (N = 22)	1.45 (1.101)	1.23 (1.066)	0.95 (0.899)	1.05 (0.999)
	1.41 (1.141)	**1.14 (1.125)**	**0.73 (0.985)**	**0.82 (1.097)**
Group 3 (N = 19)	0.32 (0.582)	0.42 (0.607)	0.32 (0.582)	0.26 (0.733)
	0.26 (0.562)	**0.16 (0.501)**	**0.16 (0.501)**	**0.16 (0.688)**
Group 4 (N = 4)	0.50 (0.577)	0.75 (0.500)	0.50 (0.577)	0.75 (0.500)
	0.00 (0.000)	**0.25 (0.500)**	**0.00 (0.000)**	**0.50 (0.577)**

In bold: taking into account taking whether the students choose "yes" or "no" correctly.

Table 11: Mann-Whitney test for comparing first and second year pre-service chemistry teachers.

Group	Task 1	Task 2	Task 3	Task 4
Group 1 (*N* = 51) first year	0.49 (0.674)	0.47 (0.612)	0.18 (0.385)	0.18 (0.385)
	0.41 (0.669)	**0.29 (0.576)**	**0.14 (0.348)**	**0.10 (0.300)**
Group 2 (*N* = 22) second year	1.45 (1.101)	1.23 (1.066)	0.95 (0.899)	1.05 (0.999)
	1.41 (1.141)	**1.14 (1.125)**	**0.73 (0.985)**	**0.82 (1.097)**
Significance	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.000$
	$p = 0.000$	**$p = 0.000$**	**$p = 0.002$**	**$p = 0.000$**
Effect size	$d = 1.165$	$d = 0.981$	$d = 1.314$	$d = 1.376$
	$d = 1.195$	**$d = 1.090$**	**$d = 0.967$**	**$d = 1.112$**

In bold: taking into account taking whether the students choose “yes” or “no” correctly.

As observed for the technical correctness, the linguistic quality is also lower for those tasks that include charged molecules. Overall, the linguistic quality decreases from task 1 to task 4; probably because the students do not see the necessity of repeating the same or similar arguments for all tasks. This will also be discussed in the limitations and conclusion and outlook sections.

As for the technical correctness, for the linguistic quality a Mann-Whitney test has been calculated (see Table 11).

The differences between both groups are statistically significant. Only small differences can be observed whether the students answered the question correct or not. The effect sizes for both cases are high ($d = 0.981$–1.376 vs. 0.967–1.195). Although not trained explicitly, the students seem to gain argumentative skills during their University study.

For the linguistic quality, the differences taking into account whether the students answered correctly or not are for both groups of tasks (without or with charge) statistically significant (see Table 12). It seems that the students’ uncertainty with charged molecules influences their argumentation. The linguistic quality is significantly better for the tasks without charges, the effect sizes are 0.345 and 0.344 and therefore in the range between a small and a medium effect.

As for the technical correctness, also for the linguistic quality between all tasks significant correlations can be observed ($r_S = 0.397^{*}$–0.673^{**} without regard to answering correctly; $r_S = 0.309^{**}$–0.639^{**} with regard to answering correctly).

The linguistic quality of students’ answers does not correlate with the technical correctness without taking into account whether the students answered the question correctly or not. If this is taken into account, small correlations can be observed for tasks 2 and 3 ($r_S = 0.280^{**}$ and 0.215^{**}). If the students answer correctly, they tend to better justify their decision. Whether the reason for this is because those students are more certain, cannot be answered by the data.

The data have also been analyzed with a focus on the problems the students have while applying the octet rule or which alternative concepts they use. They often mix up features from ionic bonds and covalent bonds, for example by writing that one atom gives the other atoms its electrons. They are not sure what valence electrons are and they confound chemical bonds with chemical compound. Both words are quite similar in German: *Bindung*

Table 12: Statistical data for both groups of tasks (pre-test; *N* = 96).

With or without regard to answering correctly	Without charge (tasks 1 and 2)	With charge (tasks 3 and 4)	Significance effect size
Without	$M = 1.30$	$M = 0.81$	$p = 0.005$
	sd = 1.516	sd = 1.316	$d = 0.345$
With	$M = 1.05$	$M = 0.56$	$p = 0.008$
	sd = 1.572	sd = 1.255	$d = 0.344$

(bonds) and *Verbindung* (chemical compound). The differences between oxidation state and charge or between charge and partial charge are also not clear. As observed before, they use the existence of a charge in the molecule for deciding that the octet rule is not satisfied, for example by writing that an electron is missing and therefore the octet rule is not satisfied.

Summarizing, the students' linguistic quality is not as could be expected. The assumption that the students are able to write a justification, because the verb "justify" is known to them from their school days could not be confirmed. One possibility is that the students knew what they should do, but were not capable of doing it for the tasks at hand. Because the linguistic quality of the students' justifications depends on whether there is a charge or not, the quality of the students' arguments seems to be influenced by their knowledge of the octet rule although there is only either a small or no correlation between technical correctness and linguistic quality. When comparing the first year major students with the first year minor students, the differences between both groups are statistically not significant.

Summarizing, the linguistic quality differs between the groups, but overall the linguistic quality is not as good as could be assumed taking into account that the students should know what to do from their own school days. This assumption is supported by the observation that the second year pre-service chemistry teachers' argumentations were rated the best, presumably because they gained the competences needed for the tasks at University and not at school.

Research question 3: how are the differences in the students' answers after the intervention?

Over all groups, 20 students participated and completed both questionnaires. Unfortunately, this represents only 20.8% of the students that participated in the pre-test. Because the courses were online (via Zoom) and the questionnaires were also provided online, there was no direct contact with the students. Explaining the study and motivating them to participate is in such a setting more difficult than in a face-to-face setting. However, some conclusions can nevertheless be drawn. Table 13 gives the arithmetic means (M), standard deviations (sd), significance (p) and effect size (d) for the technical correctness of all tasks. A Mann-Whitney test for comparing pre- and post-test also has been calculated (see Table 13).

For the students who participated in both pre-and post-test the results are positive; the arithmetic means for all tasks are significantly higher in the post-test than in the pre-test, regardless whether the students answered correctly or not. For task 4, the difference is the most significant; $p = 0.004$ without taking into account whether the students answered the question correctly and even 0.002 if this was taken into account. The effect size is then 1.126 and therefore large.

For comparing the two tasks without charge with the two tasks with charge, for both groups of tasks all statistical data have also been calculated (ratings of the tasks have been added; scale therefore between 0 and 4); see Table 14.

Table 13: Statistical data for the technical correctness of all tasks (pre-and post-test; $N = 20$).

	Task 1	Task 2	Task 3	Task 4
Pre-test; *M* (sd)	1.45 (0.826)	1.00 (0.918)	0.95 (0.999)	0.95 (0.945)
	1.25 (0.910)	**0.90 (0.968)**	**0.75 (0.967)**	**0.85 (0.933)**
Post-test; *M* (sd)	1.90 (0.308)	1.50 (0.688)	1.50 (0.761)	1.75 (0.639)
	1.85 (0.489)	**1.20 (0.951)**	**1.40 (0.883)**	**1.75 (0.639)**
Significance	0.045	0.077	0.076	0.004
	0.013	**0.323**	**0.035**	**0.002**
Effect size	0.722	0.616	0.619	0.992
	0.821	**0.313**	**0.702**	**1.126**

In bold: taking into account taking whether the students choose "yes" or "no" correctly.

Table 14: Statistical data for both groups of tasks (pre-and post-test; $N = 20$).

With or without regard to answering correctly	Without charge (tasks 1 and 2); *M* (SD)	With charge (tasks 3 and 4); *M* (SD)
Without pre	2.45 (1.504)	1.90 (1.410)
Without post	3.40 (0.754)	3.25 (1.251)
With pre	2.15 (1.599)	1.60 (1.569)
With post	3.20 (1.005)	3.15 (1.309)

Table 15: Technical correctness for "Without charge" or "With charge" (pre/post).

With or without regard to answering correctly	Without charge (tasks 1 and 2)	With charge (tasks 3 and 4)
Without pre/post	$p = 0.038$	$p = 0.002$
	$d = 0.799$	$d = 1.013$
With pre/post	$p = 0.032$	$p = 0.001$
	$d = 0.786$	$d = 1073$

The differences between both groups of tasks are statistically not significant. Therefore, the comparison of the pre-and post-tests between "with or without regard to answering correctly" has been calculated for both groups of tasks (see Table 15).

Regardless whether the students answered the questions correctly or not, for the tasks with charge, the differences between the pre- and the post-test are statistically significant. The students use the intervention as learning opportunity especially for the tasks with charged molecules. For teaching the subject "octet rule" this means that charged molecules should be in the focus and the application of the rule for such molecules should be taught and trained explicitly (Table 16).

The differences between the pre- and the post-test are statistically not significant. This is not surprising, because the training of argumentation skills was not the main focus of our study. For future teaching, this should be taken into account. As discussed in the literature (Lieber et al., 2022b), argumentation skills can be trained explicitly.

As for the technical correctness, for the linguistic quality the data taking into account whether the students answered the questions correctly or not have been calculated (see Table 17). The differences between both groups of tasks are also statistically not significant.

Table 16: Arithmetic means and standard deviations for the linguistic quality of the justifications of all tasks (pre-and post-test; $N = 20$).

Group	Task 1	Task 2	Task 3	Task 4
Pre-test	1.00 (0.973)	0.80 (0.951)	0.65 (0.988)	0.80 (1.105)
	0.90 (1.021)	**0.65 (0.988)**	**0.45 (0.999)**	**0.70 (1.129)**
Post-test	1.20 (1.196)	0.95 (1.317)	0.75 (0.967)	0.80 (1.005)
	1.20 (1.196)	**0.85 (1.348)**	**0.65 (0.988)**	**0.80 (1.005)**

In bold: taking into account taking whether the students choose "yes" or "no" correctly.

Table 17: Arithmetic means and standard deviations for the linguistic quality of the justifications for both groups of tasks (pre-and post-test; $N = 20$).

With or without regard to answering correctly	Without charge (tasks 1 and 2); *M* (sd)	With charge (tasks 3 and 4); *M* (sd)
Without pre	1.80 (1.673)	1.45 (2.012)
Without post	2.15 (2.231)	1.55 (1.877)
With pre	1.55 (1.820)	1.05 (1.905)
With post	2.05 (2.235)	1.45 (1.877)

Summarizing, the small intervention was successful as all students' results were better in the post-test than in the pre-test. The results for task 4 were statistically most significant. This supports our observation that the students have difficulties with applying the octet rule to charged molecules. However, if the students have the opportunity to train this application, as in this intervention, their competences increase.

Limitations

There are some limitations to this study. Four different groups of students participated. The number of students in those groups is not equal, but differs between 4 and 51 (pre-test) and for the post-test between 0 and 10. The total sum of participants for the pre-test is with 96 students much higher than for the post-test where only 20 students participated. For comparing pre- and post-test only those 20 students were taken into account. Although the students gained in competence from pre-to post-test, it remains unclear whether the students who did not participate in the post-test also gained in competence for the application of the octet rule. Because the linguistic quality decreases from task 1 to task 4 it cannot be excluded that the results of the latter tasks depend on the previous tasks if the students do not see the necessity for repeatedly explaining the application of the same rule. The observation that the students have difficulties with applying the octet rule for charged molecules has been confirmed by this study. However, the last example was the only example for an organic molecule. Whether this also influenced the students' application of the octet rule cannot be answered by our study.

Conclusions and outlook

Students have problems with the application of the octet rule, especially for charged molecules. The evaluation of the students' explanations also shows that their knowledge on the different types of chemical bonds (ionic or covalent) is not sufficient as the following quote makes clear: *"the nitrogen atom still has one bond free, therefore the shell is not completely occupied and the octet rule is not satisfied"*. Here, the student mixes up knowledge on the ionic bond with the octet rule, which has been repeatedly observed in this study. Although the students' competences on the application of the octet rule were better after the intervention, future teaching should explicitly focus on the application of the octet rule for drawing Lewis structures. This could be combined with the training of argumentation skills, because the results of this study also show that the students have difficulties with explaining their choices.

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