

Article

# Between Symbols and Particles: Investigating the Complexity of Learning Chemical Equations

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**Abstract:** This study explores the pedagogical challenges in teaching chemical equations, focusing on the ability to balance chemical equations and understanding related basic chemical concepts among chemistry teacher students. Based on Johnstone's representation theory, we examined the efficacy of digital tools designed to enhance equation-balancing skills. The key findings of this study seem to be the disconnection between students' procedural proficiency in balancing equations and their conceptual understanding of underlying chemical reactions. Surprising was the relatively low ability to balance chemical equations when compared to the expected level of upper-secondary school students. An analysis of the results showed that students could be distinguished into four different groups of solvers based on their total score and solving time: efficient, persistent, impulsive, and inefficient solvers. Utilizing an eye-tracking study, the findings reveal a predominant reliance on symbolic representations, with additional sub-microscopic representations provided by digital applets failing to significantly improve equation-balancing capabilities. This reliance potentially hinders students' ability to conceptualize reactions at the particulate level, impacting overall chemistry comprehension. This study underscores the need for a pedagogical shift toward integrating multiple representations into chemical education to bridge the gap between procedural skills and deep conceptual understanding. By highlighting the limitations of current teaching approaches and the use of digital tools, this research contributes to improving chemical education strategies, fostering a more integrated and nuanced understanding of chemical principles among students.



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**Keywords:** chemical equations; chemistry education; pre-service teacher training

## 1. Introduction

One of the central paradigms of chemical education has become the idea proposed by A.H. Johnstone in 1982 [1], which suggests that all chemical understanding of the world around us can be expressed at three different levels: macroscopic, sub-microscopic, and symbolic. This concept has been further refined and expanded over the years (see, for example, [2,3]). Each representation for chemistry learners presents a different level of difficulty, requiring complexity and versatility. This fact is often interpreted as a reason for the poor attitudes of students toward chemistry and, by extension, the natural sciences, and has become a widely studied topic [4–8], especially because of its impact on their academic results [9,10] but also, of course, on their future aspirations (further studies or a career in the field).

In her literature review, Flaherty [11] highlighted the importance of this research for understanding the challenges faced by chemistry educators in their efforts to improve students' attitudes toward chemistry. Studies focusing on identifying the causes of students' negative attitudes toward the natural sciences (for example, [12–16]) emphasize the need for a deeper analysis of the factors such as abstractness, perceived difficulty, low sense of applicability, etc., leading to these attitudes and the search for effective strategies for their change.

One of the classic chemistry topics identified as critical [16], possibly due to the need for linking the three representations, is chemical reactions expressed in the form of chemical equations.

Ben-Zvi and Genut [17] and Yarroch [18] found that chemical equations do not activate a similar integrated understanding in students as they do in chemists (scientists). Although most students can interpret a chemical reaction using macro-level representations [19,20], the use of symbols dominates in the school environment [21]. This practice results in some students imagining a chemical equation more as a mathematical puzzle rather than symbolizing a dynamic and interactive process.

Aspects of symbolic representation that are familiar and taken for granted by “experts” (i.e., chemists, science teachers, etc.) may not always be well understood by students, even at the university level [22]. Their ideas about the meaning of symbols in chemical equations can be imprecise or completely incorrect [22,23].

However, teachers most often use the symbolic level of representation in chemistry teaching [21], which further confirms the influence of textbook design and content on teaching (cf. [24]), since symbolic representations dominate in textbooks [25–28]. The representation of reactions using sub-micro particles is thus neglected [29,30]. When students were asked to explain their symbolic notation using sub-microscopic representations, a number of misconceptions emerged [29]. Several recent studies, rather than helping students understand the true meaning of chemical equations, showed a tendency to tackle the balancing part [31,32]. This suggests that further work with chemical equations, whether balancing them or calculations from chemical equations, tends to be empty algorithms in terms of counting with imaginary symbols without a deeper understanding of concepts, rather than following a description of real chemical substances, i.e., building on an understanding of concepts (cf. [33]). This gap, if not overcome, is likely to hinder all quantitative areas of chemistry.

From the perspective of chemistry studies, students need to master the topic of chemical reactions, including stoichiometry, throughout their course of study. Insufficient ability to work with chemical equations can, among other things, lead to complications in practical laboratory work, which is an integral part of studying chemistry (see e.g., [34]). For this reason, this topic deserves further attention.

## 2. Theoretical Background

### 2.1. Chemical Equations as a Part of Chemical Education

Krajcik [35] refers to a persistent problem in chemistry education, where it was found that even after a year of chemistry education, high-school students lack a conceptual understanding of basic chemical concepts [18,36–40]. The emphasis on factual information does not lead to conceptual framework development, as scientific knowledge is often very different from personal experience—chemical concepts become a list of memorized facts that students recall during exams [35]. Chemistry becomes abstract [41,42] and difficult, leading to practice in handling formal tasks based on memory rather than the ability to solve scientific problems [43].

For a deep understanding of chemistry, it is essential to acquire knowledge about chemical and physical changes, the particulate nature of matter (PNM), the kinetic molecular theory, and the interactive and dynamic aspects of chemical reactions. As Krajcik [35] emphasizes, developing an integrated understanding of these concepts (see [44]) is fundamental for understanding a wider range of chemical concepts. This approach supports a comprehensive understanding of chemistry, which is crucial for success in study and scientific practice. However, this aspect of (chemical) education is complicated by the fact that students do not find themselves in the stage of formal thinking (cf. [45–47]) required for understanding chemical concepts at the sub-micro level [48,49].

Chemical equations, as a basic tool for expressing principles and procedures, represent not only a central element for understanding the course of chemical reactions and the ratios between reactants and products; they also play a key role in further expressing quantities

of reactants through chemical calculations. Macroscopic representations serve only a little; therefore, the sub-microscopic and symbolic are dominant.

Although the symbolic level is necessary in chemical education, it cannot be considered principal. Symbolic notation is merely a means of communication, while understanding the principle of a reaction requires understanding the interactions on the sub-microscopic level. It includes electrons, molecules, atoms, ions, and other particles that are real but too small to be observed by the naked eye [50]. The mere use of symbols can complicate the understanding of deeper chemistry concepts. The choice of representations is important to consider carefully, as their overabundance can lead to student overload and be inefficient [51].

As mentioned in the introduction, in practice, however, the symbolic level is the main representation used [21]. This leads to formalisms, as in the case of the periodic table (see [52])—the original concept of a chemical equation, instead of documenting the reaction in school practice, transforms into a separate skill or a subject matter chemistry learners need to acquire [18,53,54]. As a result of teaching, students may be able to balance the equation, but most chemistry students do not develop a conceptual understanding of chemical reactions as such. The original goal thus shifts to scholastic formalisms [55,56].

This approach was observed in recent work by Méndez Gutiérrez, et al. [31], who even offer the further simplification of equation balancing by providing students with an algorithm using “practical steps and not so complicated mathematical operations”. In the same spirit, Hussien, et al. [32] offer a solution through a computer program that balances the equation for students. In such cases, however, there appears a reversal of the position of chemical equations. From a support in the form of notation, they become the subject matter or an artificial problem. The goal is no longer to capture the course of the reaction but to balance the equation, which has little to do with chemical concepts.

## 2.2. Students' Chemical Equations Abilities

In accordance with the debate mentioned above regarding the formal approach to chemical equations within chemical education, previously published studies unanimously indicate problems that have persisted for 40 years. Yaroch [18] noted that despite all observed students being able to balance the equations, discrepancies emerged in their understanding of the balancing rule and presented concept. This indicates a need for instructional approaches that enhance both procedural and conceptual understanding. Similarly, the research by Ahtee and Varjola [53] examined students' conceptual understanding of chemical reactions. It found significant gaps in students' ability to accurately describe a chemical reaction, highlighting a mixture of sound, partial, and incorrect understandings. The study emphasized the need for improved instructional strategies to better address students' misconceptions and enhance their grasp of fundamental chemical concepts. Similar findings have been brought forth in recent years by Jammeh, et al. [57] and Naah and Sanger [58], suggesting that the problem still persists and the way this area of chemistry content is taught has not changed.

In another paper, Sanger [54] explored high-school and freshman college students' understanding of chemical equations and stoichiometry. They revealed that students often confuse subscripts and coefficients in chemical equations, indicating a gap between solving mathematical problems and understanding underlying chemical principles. The research suggested that instructional strategies should focus on bridging this gap to enhance students' conceptual grasp of chemistry.

The problem with understanding chemistry equations was also revealed in Rusek et al.'s [34] study. College students struggled with even simple equations when faced with stoichiometry problems. Since these were students who had chosen chemistry as their field of study in higher education, this conclusion is alarming and points to a failure in current practices in this regard.

As stated above, a starting point for improving this situation could be the effort to complement symbolic representations with other representations. One of the available

environments that offers this is PhET interactive simulations. In this environment, research by Hansen [59] revealed that when using models, success in tasks in the applet environment focused on stoichiometry was higher than if students did not use them or used them to a lesser extent. Similarly, Davidowitz, et al. [60] monitored the effect of engaging models on students' ability to work with equations. They argued that using models on the sub-microscopic level provided students with sufficient support to consider the complete picture of reactions, including their stoichiometry.

An alternative to Hansen's [59] study using eye-tracking was conducted by Baluyut and Holme [61], who used similar methods to map students' work with equations and the representation of their particles. They found that successful students spent more time studying the particles' models and made more transitions at the sub-microscopic level.

Overall, these studies collectively underline the importance of innovative and interactive teaching methods, addressing misconceptions, integrating technology, emphasizing conceptual understanding over rote learning, and recognizing the role of mathematics in chemistry education. The implications call for a more nuanced and student-centered approach in chemistry teaching to provide materials more suited to students' diverse preferences or even learning styles, as they thrive when using multiple representations (see e.g., [42]).

This call for the use of the most modern technologies in teaching complex chemical concepts, which requires the integration of multiple modes of representation, is accentuated by the latest studies focusing on the use of technology—not only in teaching chemistry but in researching chemical concepts. An applet for balancing chemical equations was also used by Carpenter, et al. [62]. In their study, students' procedures were captured through the analysis of student interviews and mouse movements. They found that students used half-remembered heuristics, which they considered absolute rules for the process of balancing.

### 3. Research Aim

The aim of this research was to map freshman chemistry pre-service teachers' procedures when balancing chemical equations in the applet PhET: Balancing Chemical Equations. Since the applet environment provides scaffolding in the form of sub-micro support, it is possible that this support may affect their performance. The causes of success and failure in balancing chemical equations could be analyzed based on students' procedure and performance, and these findings may lead to implications for chemistry instruction.

The study pursues the following research questions:

RQ1: How successful are chemistry pre-service teachers in balancing chemical equations at the beginning of their studies?

RQ2: What affects students' success rate in balancing chemical equations?

RQ3: What approaches do students choose when balancing chemical equations?

RQ4: How do students use the applet environment while balancing chemical equations?

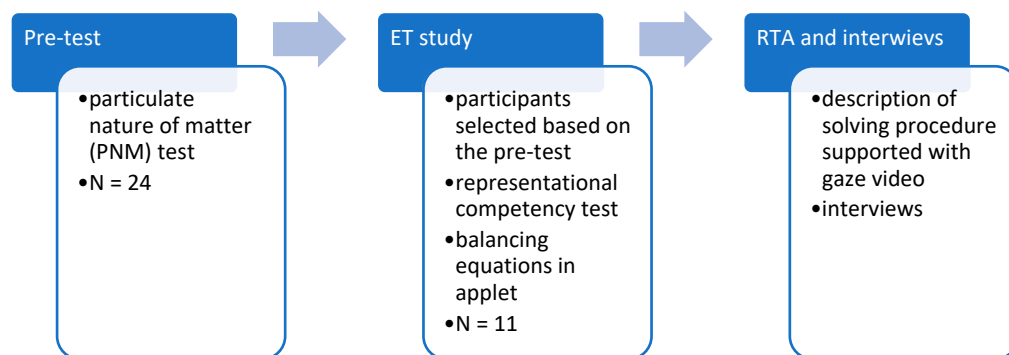
### 4. Materials and Methods

#### 4.1. Research Sample

This research was conducted on a group of chemistry teacher students ( $N = 24$ ) in their freshman year during the first semester of their studies at the Faculty of Education (Charles University). The original sample included students studying a chemistry teaching program in combination with biology, mathematics, German, health education, or IT.

#### 4.2. Research Procedure

The research combined eye-tracking (ET) with retrospective think-aloud (RTA) and interviews and consisted of several phases—see the research design in Figure 1.



**Figure 1.** Research design.

At the beginning of the 2021/2022 academic year, the students were given the PNM test. Based on the test's results, 12 students were selected to represent successful, partly successful, and unsuccessful solvers (four students in every category)—an approach that has proven useful when needing to study the procedures of solvers at various skill levels in depth while maintaining a manageable and processable amount of data [43,63]. Eleven participants agreed to take part in the follow-up study. The research sample of eye-tracking studies typically ranges from 1 [63] to over 600 [64]. Purely quantitative studies usually involve more participants, while studies combining multiple methods (e.g., think-aloud and interviews) may consider the sample used in this study to be sufficient (see for example [43,63,65]).

To obtain more data about students' conceptual understanding of chemical reactions and chemical equations, they were given another pre-test (representational competency test), which they answered orally.

The selected students balanced six chemical equations in the environment of the PhET applet. The number of equations for balancing was chosen with consideration for the appropriate duration of a single measurement. The students were not given a specific time to balance the equations as it was seen as an unnecessarily added stress factor. Their eye behavior was recorded by an eye-tracker. Cued RTA protocols completed with interviews followed. Each session lasted approximately 50 min.

Before the measurement started, the respondents were introduced to the applet environment and tried working in it with examples of simple equation-balancing tasks. The purpose of the study and the measurement process were explained to them. All participants were asked to consent to the recording of their eye movements, the think-aloud, and interview.

After calibration, the applet PhET: Balancing Chemical Equations was launched. Participants balanced six chemical equations at three different levels of difficulty. A computer mouse was used by participants to navigate in the applet.

After completing the measurement, participants were replayed their eye-tracking record and encouraged to describe their solving procedure (cued RTA, see, e.g., [66]). After RTA, researchers asked additional questions when more explanation was needed. This approach was chosen as students might not have sufficient metacognitive skills to describe their procedures (cf. [67]). To obtain sufficient information, interviews followed each session; they included questions regarding respondents' opinions on the applet environment and difficulty of the chemical equations, algorithms used in balancing, and their previous experience of learning to balance chemical equations at secondary school (or at a previous university, if applicable).

The combination of these methods allowed us to obtain complex information about influences on freshman students' ability to balance chemical equations.

#### 4.3. Equipment

The eye-tracker Tobii Fusion Pro with a 250 Hz sampling rate was used for recording respondents' eye behavior. The camera was placed under the computer screen (resolution:

1920 × 1200) used by the participants. This set-up allowed for free head movement to a point. Nine-point calibration was performed prior to every recording.

#### 4.4. Research Tools

The respondents were given two pre-tests: the PNM test and representational competency test.

The PNM test was taken from Hansen [59], translated and expanded with one item, which tested model-based understanding of the concept of a chemically pure substance. In total, it contained 16 items, with each correctly answered item being scored one point. The test included only multiple-choice questions, and only one answer was correct. Knowledge and understanding of the definitions and characteristics of the basic concepts in the field were tested: knowledge of the terms: atom, molecule, element, chemically pure substance, compound, mixture, solution, chemical bond, and chemical transformation, and conceptions of the law of conservation of mass.

The representational competency test consisted of four tasks focusing on chemical equations and chemical reactions using different chemical representations. This test was taken from Hansen [59] as well. The content of these tasks included a verbal description of a balanced chemical equation; a verbal description of a chemical reaction using pictures of substances, models and formulas; balancing equations based on a written description of the reaction; and the conversion of a sub-micro diagram of a chemical reaction into a balanced equation.

An applet, PhET: Balancing Chemical Equations, was used for the next part of the eye-tracking study. Students balanced six chemical equations at three different levels of difficulty. The levels are differentiated in the applet based on the number of reactants or products as well as the value of the stoichiometric coefficients needed. An expert panel of chemistry educators verified that the classification of the equations into the levels of difficulty in the applet corresponds to the number of steps required to balance them.

In the applet environment, there is a notation of an unbalanced equation (symbolic representation) and a representation of reactants and products (sub-micro representation). In the Introduction part, users also have support in the form of scales or bar charts showing the ratio of atoms. The user starts with an equation where all stoichiometric coefficients are 0. Using the arrows, the coefficients can be added or subtracted step by step. The applet displays the corresponding number of model molecules. When the user considers the equation to be balanced, he/she allows it to check. Feedback is then given on whether the equation has been balanced correctly. A correct solution is scored two points. If the equation is incorrectly balanced, the balancing continues. A successful corrective attempt is scored one point. If the equation is not correctly balanced during this attempt, no points are received.

The first two (the simplest) equations on level 1 in the Introduction part served to acclimatize the participants with the environment. All respondents balanced an equation of the synthesis of ammonia and the combustion of methane. The following four equations were taken from the main part of the applet (named "Game"). Two were on level 2 (Equation (1)—E1, Equation (2)—E2) and typically included two reactants and two products. The two equations on level 3 (Equation (3)—E3, Equation (4)—E4) were the most difficult due to higher interfering stoichiometric coefficients with the same number of products and reactants. As the applet selects the equations in the Game part randomly, some respondents balanced different equations to others. In total, we observed students balancing 10 different equations on level 2 and seven different equations on level 3. Nevertheless, since the equations' balancing required a corresponding number of steps, these were considered comparable.

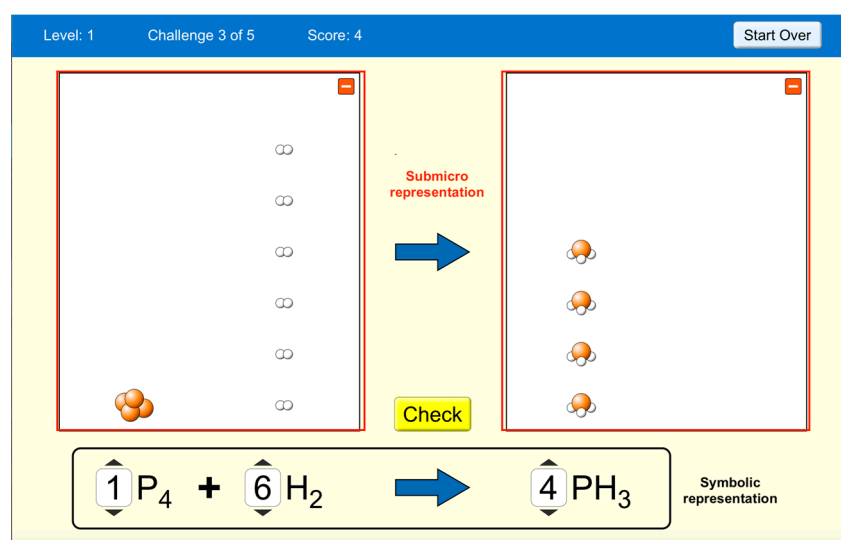
## 4.5. Data Analysis

### 4.5.1. Tests

Items in the PNM test (see the Supplementary Materials) were awarded one point for each correctly chosen answer. Oral responses to the representational competency test tasks were transcribed verbatim and assessed for correctness, with each correct answer receiving two points and partly correct answers receiving one point. Special attention was given to items that examined the conceptual understanding of the law of conservation of mass, the comprehension of sub-micro representations, and the ability to state the quantities of substances in a chemical equation. The students' performance in these areas was later compared with their ability to balance chemical equations.

### 4.5.2. Eye-Tracking

Data processing was conducted using Tobii Lab Pro software. Due to the issue of utilizing individual components of used applets, Areas of Interest (AOIs) were employed. The pre-defined AOIs included the area of the chemical equation and the blocks displaying its sub-micro representation (models) (see Figure 2).



**Figure 2.** The applet environment and analyzed AOIs.

To analyze students' focus in AOIs, the eye-tracking metric—total fixation duration (TFD)—was calculated as a ratio of TFD on the sub-micro representation AOI to the overall TFD on a stimulus.

A critical aspect that leveraged eye-tracking technology was the examination of students' approaches. For this purpose, gaze videos—that is, the tracking of fixations during equation balancing—were utilized. These records were translated into a sequence of steps by researchers for subsequent analysis. Additional insights were gained from the RTA and interviews transcribed verbatim. Subsequently, open coding was conducted using QDA Miner Lite to identify both similar and divergent strategies in balancing chemical equations. ChatGPT's Data Analyst tool was further employed to provide a qualitative analysis of the students' procedural descriptions.

### 4.5.3. Statistical Analysis

The data were processed using traditional methods of statistical analysis. For continuous data, normality was assessed with the Shapiro–Wilk test. If normality was not rejected, parametric tests were applied; otherwise, non-parametric tests were chosen. The primary analysis tool was IBM SPSS 26, complemented by effect-size calculations performed using an online calculator at ai-therapy.com. Pearson's correlation coefficient ( $r$ ) was used to evaluate the relationships between test scores and both the computation and time required

to solve equations. For most paired data, the Wilcoxon test was employed, using  $r$  as the effect-size indicator. The effect sizes were interpreted as follows: an  $r$  value of less than 0.3 indicates a small effect, 0.3 to 0.5 indicates a medium effect, and greater than 0.5 a large effect [68]. The McNemar test, with Cramér's  $V$  as the effect size, assessed differences in scores, with effect-size interpretations to be specified. For parametric data, ANOVA was utilized along with Cohen's  $d$  for effect size, which also requires specific interpretation guidelines [68].

## 5. Results

The performance of students in balancing equations ranged from four to eight points, i.e., a success rate of 50–100%, as shown in Table 1. Only five students achieved the highest score. Six respondents made one or more mistake during the equation-balancing process. One student, in the case of one level 3 equation (E3), made a correction once, resulting in a lost point; however, this student can still be considered successful in terms of the ability to balance equations. Conversely, one student only achieved half of the possible points, failing to balance two equations of differing difficulty levels (E1, E4) correctly, even with correction attempts.

**Table 1.** Students' scores in balancing chemical equations in applet.

	E1	E2	E3	E4	Total Score	Overall Success Rate
Student 1	2	2	2	2	8	100%
Student 2	2	2	2	2	8	100%
Student 3	2	2	2	2	8	100%
Student 4	2	1	1	2	6	75%
Student 5	2	2	0	2	6	75%
Student 6	2	2	2	2	8	100%
Student 7	2	2	1	2	7	88%
Student 8	0	2	2	0	4	50%
Student 9	1	2	0	2	5	63%
Student 10	2	2	2	2	8	100%
Student 11	1	2	0	2	5	63%

The remaining students made errors in one or two equations. These students managed to correctly balance at least one equation during a correction attempt. An exception is one student who erred once but failed to correctly balance the given equation.

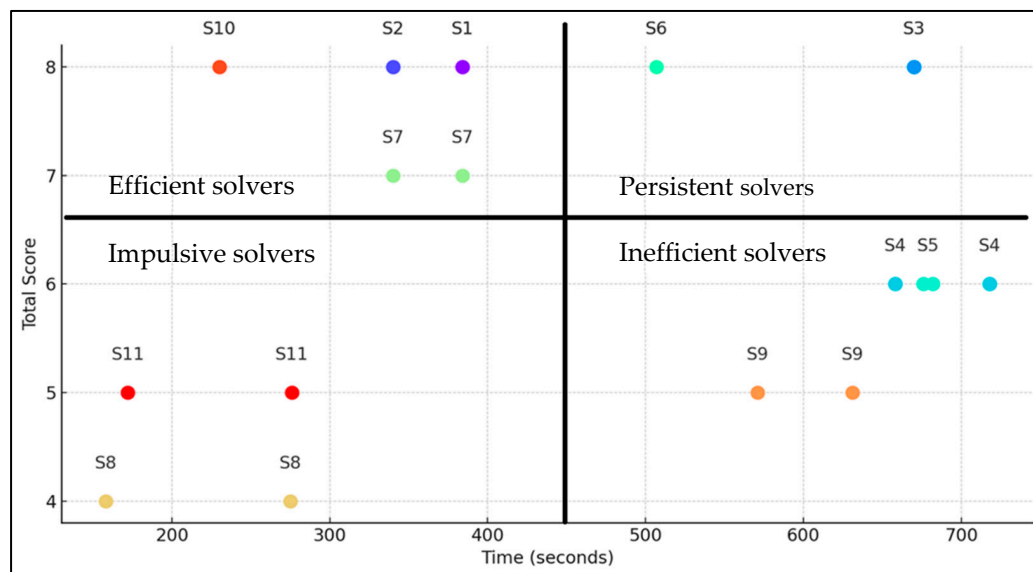
### 5.1. Success Rate and Time to Balance Chemical Equations

The relationship between the time spent balancing equations and overall success is depicted in Figure 3. For respondents who needed to correct the stoichiometry of chemical equations, both the total time excluding correction attempts and the total time including time spent on corrections are presented, utilizing two different points.

Overall, a clear correlation between time spent and overall success was not demonstrated ( $r = 0.0197$ ). Respondents can be categorized into four quartiles based on their success and the time needed for solution (see [69]).

Students 1, 2, 7, and 10 were successful and required a relatively short amount of time for solutions. They can be labeled as efficient solvers. These solvers demonstrated efficiency in balancing chemical equations by applying a clear and functional procedure, as evident from the eye-tracking records and retrospective think-aloud sessions and interviews.

Students 6 and 3 achieved 100% success in balancing equations but took longer than the first group of solvers. This result characterizes them as persistent solvers. Their initial approach was not efficient, but upon review, they continued with balancing until they arrived at the correct solution. Only after verifying their solution did they confirm it, thereby not losing any points. The eye-tracking records and interviews reveal that during the process they were able to correctly identify that the stoichiometry in the equation did not match the correctly balanced form of the equation.



**Figure 3.** The dependence between total time and total score.

Students 8 and 11 achieved low results in a short time, indicating that they are solvers with a quick but ineffective approach to balancing equations. Their haste was observable during the initial attempts, when both made mistakes in one equation at both levels of difficulty. These respondents seem to rush the process, not spending enough time on considering the steps needed for balancing equations on the particulate level of difficulty or enough time on checking their work. They can be labeled as impulsive solvers, whose approach reflected on their overall score.

The fourth group comprises students 4, 5, and 9, who also achieved low scores over a long duration. They are inefficient solvers. These solvers invested significant effort and time in balancing equations, but in some instances, their methods proved inefficient. It was observed that their correction attempts were shorter than those of impulsive solvers, reflecting their approach to solving. While impulsive solvers were very quick during the first attempt and devoted time to correction attempts, inefficient solvers demonstrated a persistent approach during initial attempts, trying to figure out the proper stoichiometry for the equation. Students 5 and 9 each gave up on continuing to balance an equation when they did not know which other method to use to achieve the correct solution.

Further insights are provided by examining the relationship between the time required for solving and the number of points earned by each student individually. Figure 4 offers information on the performances of students in balancing two equations on level 2 (these equations involved two reactants and two products, with no stoichiometric coefficient higher than 3). The columns representing the time taken to solve the first equation (E1) and the second equation (E2) are also color-differentiated, distinguishing between the first attempt and the correction attempt. The success of balancing each equation, in terms of points, is indicated by a colored dot in the graph.

The data indicate that the solving time for most, specifically five, successful respondents in both equations was below the average time. For the remaining two, the solving time of at least one equation was longer than the average. The times of the first unsuccessful attempts uniformly occurred both above and below the average.

Therefore, the solving time is not the sole determinant of failure in balancing equations, further underscoring the need for a more comprehensive analysis of the procedure.

In balancing level 2 equations, a trend was observed among successful solvers toward a faster resolution of the second equation (in six cases out of eight). For two solvers, the time increased, with one of them also requiring a correction attempt. Conversely, students who were not successful in balancing the first equation on the first attempt spent more time on the subsequent equation than before. The Wilcoxon paired test was used to compare

the solving times of the first and second equations. No statistically significant differences were found in the solving times of the first and second equations within level 2 ( $p = 0.1475$ ). However, the effect-size value indicates a medium effect ( $r = 0.437$ ) in the difference in solving times between the first and second equations within difficulty level 2.

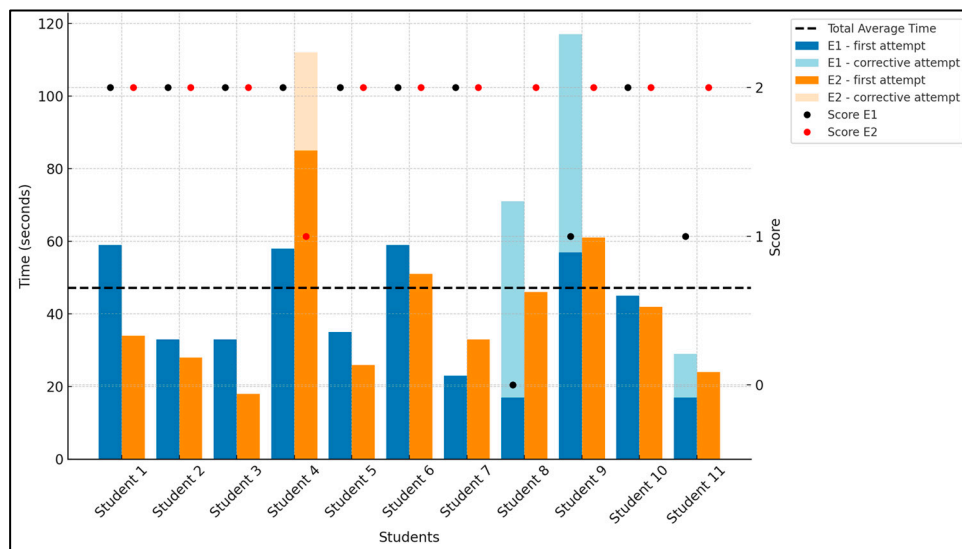


Figure 4. Students’ performance in balancing chemical equations on level 2.

An analysis of the time spent on corrections reveals a significant increase in total solving time. For students 8 and 9, their correction attempt time was longer than the first attempt time. Three out of four correction attempts were effective. It is evident for student 8 that even during a significantly long correction time, the equation was not balanced correctly.

The effect of effort expended on the success of balancing individual equations was monitored. Pearson’s coefficient results suggest that a longer time spent balancing the first equation corresponded to lower student success for that equation ( $r = 0.464$ ), considering the total solving time including corrections. However, an interesting result emerged when considering only the time of the first attempt, i.e., when respondents considered their result correct. In this case, a longer time on the first level 2 equation corresponded to higher success ( $r = 0.445$ ). Given the sample size, these results should be treated with caution.

The performance of students in balancing level 3 equations is illustrated in Figure 5.

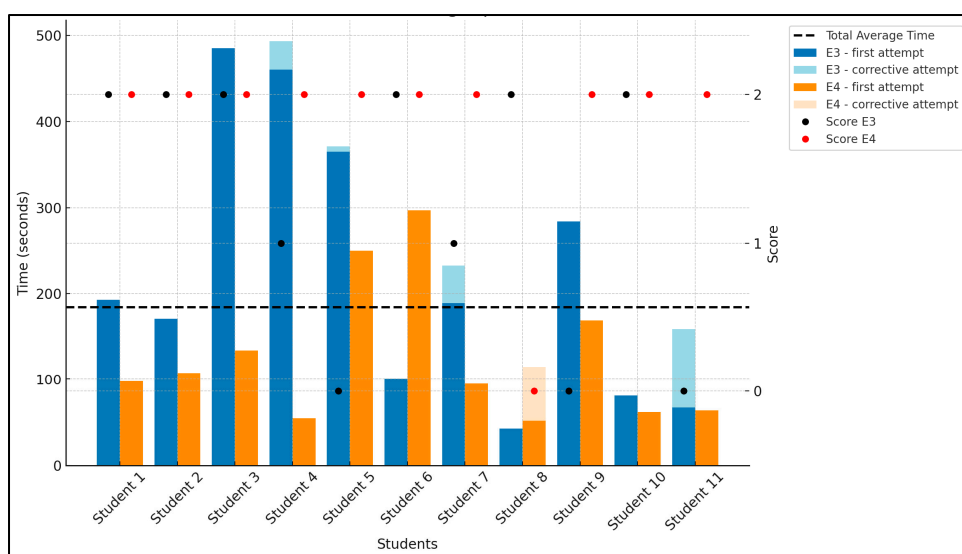


Figure 5. Students’ performance in balancing chemical equations on level 3.

The solving times for level 3 equations were much longer compared to level 2 equations and varied significantly among respondents. Those whose solving time was below the average were considered successful, as were those who devoted a large amount of time and effort to balance chemical equations.

For four out of six students who correctly balanced the first equation, the time to solve the second equation at the same level decreased. The solving time for the second equation was also shorter for all five students who made mistakes in the first equation, with only two experiencing an increase in solving time. Although no statistically significant difference was found between the solving times for the first and second equations at level 3 ( $p = 0.0674$ ), the effect-size value ( $r = 0.551$ ) indicates a large difference. At this level, it was noticeable that students were able to apply experiences from balancing the previous equation to the second equation based on solving times.

Five students failed to balance the first equation (E3) of level 3 on the first attempt. One student made a mistake in the second equation. Their success generally increased when balancing the second equation. No statistical differences in equation-balancing success within this level were proven ( $p = 0.219$ ), but the effect size (Cramér's  $V = 0.4$ ) was medium.

In four out of six cases, students were unable to balance the equation even after correction. Impulsive solvers spent more time on correction than the remaining erring respondents, yet their overall score for the respective equation remained zero. Two inefficient solvers gave up on correction without attempting a solution. Respondents 4 and 7 were successful in their correction attempt.

A correlation between the time spent balancing and the success of students in the first equation at level 3 was observed. When comparing the total time including correction attempts ( $r = 0.324$ ) and the time of first attempts only ( $r = 0.217$ ), higher success was associated with longer solving times. This contrasts with level 2, where the effect was opposite for the first attempts.

In a comprehensive comparison of student performance in balancing equations at levels 2 and 3, both the time spent balancing the equation and the points earned were considered. It was evident that with the increase in difficulty level, there was a significant increase in the time needed to balance the chemical equation and a decrease in success. The solving times for equations at level 2 were statistically significantly shorter than at level 3 (E1 and E3  $p = 0.004$ ,  $r = 0.735$ ; E2 and E4  $p = 0.008$ ,  $r = 0.749$ ), suggesting a strong effect size for both observed differences. While no statistically significant difference was found in total point scores ( $p = 0.134$ ), the effect size (Cramér's  $V = 0.535$ ) showed a large effect.

Eye-tracking data provided information on the number of saccades (movements of the eyes between points of fixation, where the eyes momentarily stop and focus) that students made while balancing equations. The number of saccades can be interpreted as the number of mental transitions students made during balancing. It was found that the number of executed saccades proportionally corresponds to the time used for balancing chemical equations. Time can be considered an indicator that corresponds to the number of steps students took during balancing chemical equations.

## 5.2. Results in the Pre-Tests and Their Relation to the Overall Equations Balancing Result

When comparing the results of the PNM test with outcomes in balancing equations, it is clear there is no direct relationship between success in the PNM test and success in balancing equations. For this reason, only items from the PNM test directly related to the concepts of chemical equations were selected. These were further supplemented with items from the representational competency test and divided into areas: law of conservation of mass, understanding of sub-micro representations, and stoichiometry.

The success of students in each area, the overall average from these areas, and their success in balancing equations are presented in Table 1. The comparison of pre-test results suggests that there is also no direct relationship between success in items related to chemical equation concepts and the success of students in balancing them.

For a more detailed analysis, correlations were calculated between the outcomes of balancing equations and individual groups of pre-test items focused on specific concepts related to chemical equations. According to Pearson's correlation coefficient, understanding stoichiometry shows the strongest positive relationship with success in balancing equations among all tested areas. A medium–strong correlation was recorded between stoichiometry and equation balancing ( $r = 0.580$ ). Understanding the law of conservation of mass also shows a medium–strong correlation with balancing equations ( $r = 0.476$ ). Conversely, understanding at the sub-micro level has a less significant impact on balancing equations ( $r = 0.275$ ).

It is evident from the table that even students who did not demonstrate a deep understanding of the concept of the law of conservation of mass, sub-micro representations, or stoichiometry can be successful in balancing chemical equations. For example, seven students scored 50% or less in the area of the law of conservation of mass but managed to apply it indirectly when balancing a chemical equation.

Further information on the impact of concept knowledge on the ability to balance equations was obtained by comparing the success of different student groups divided according to balancing-equations results. Students were divided into groups based on a test score that considered not only the total number of points but also the difficulty of balancing equations. As equations on level 3 were more complicated, successful solvers received more points for them. The weighted score reflecting the level of difficulty of chemical equations was calculated as follows:

$$\text{Score} = (\text{score E1} \cdot 1) + (\text{score E2} \cdot 1) + (\text{score E3} \cdot 2) + (\text{score E4} \cdot 2) \quad (1)$$

To compare some more characteristics, the students were divided into three groups:

- Group 1—successful students 1, 2, 3, 6, 10;
- Group 2—average students 4, 5, 7;
- Group 3—unsuccessful students 8, 9, 11.

Further analysis showed that the differences among the groups may be a result of their different pre-test scores. For the items “understanding sub-micro” and “balancing equations”, the Shapiro–Wilk normality test results for the pre-test dataset and the total points in balancing equations allowed for the rejection of the null hypothesis regarding non-normal distribution. Consequently, the Kruskal–Wallis test was utilized with eta-squared as the effect size for these items, while ANOVA and Cohen's  $d$  were used for the remaining items.

In terms of outcomes in the overall pre-test, students in the unsuccessful group achieved poorer results compared to the rest of the students. Although this difference was not statistically significant, the effect-size values indicated a medium to large effect between the successful and unsuccessful ( $d = 1.238$ ) and between the average and unsuccessful ( $d = 1.9211$ ). Concrete field-specific differences among the groups were found when their test score from key concept test was evaluated. The student groups differed significantly ( $p = 0.0078$ ). Cohen's  $d$  suggested a large difference ( $d = 0.9697$ ). However, the effect-size indicated a small to medium effect between successful and average groups and between average and unsuccessful groups, and a large effect between successful and unsuccessful Groups 1 and 3 ( $d_{12} = 0.2697$ ,  $d_{13} = 1.2810$ ,  $d_{23} = 0.8660$ ) in understanding the law of conservation of mass. Furthermore, a medium to large effect was found between successful versus other solvers ( $d_{12} = 1.3148$ ,  $d_{13} = 1.5365$ ) in understanding the stoichiometry of chemical equations.

### 5.3. Use of the Applet Environment

Eye tracking allowed us to identify areas in the applet that the students focused on. Students spent 97.3% of the time fixating on the symbolic area with the equation itself.

Overall, a medium-strength negative correlation ( $r = -0.500$ ) was observed between the time spent using sub-micro support and success in balancing chemical equations. The

more time respondents spent using sub-micro support, the less successful they were. For the first equations, which were problematic for a larger number of respondents at both levels, a strong ( $r = -0.726$ ) and a medium-strong ( $r = -0.530$ ) negative correlation could be noted at level 2 and level 3, respectively. Sub-micro support was most utilized in the first equation (E1) and the ratio of TFD was 4.7%, which means 1.8 s (see Table 2).

**Table 2.** Respondents' success rate in selected areas.

	Law of Conservation of Mass	Understanding of Sub-Micro	Stoichiometry	PNM Test Sum Score	Balancing Equations
Student 1	100%	100%	80%	93%	100%
Student 3	75%	100%	100%	92%	100%
Student 4	75%	75%	80%	77%	75%
Student 2	50%	100%	60%	70%	100%
Student 7	75%	75%	40%	63%	88%
Student 10	50%	50%	80%	60%	100%
Student 8	50%	100%	20%	57%	50%
Student 6	50%	50%	60%	53%	100%
Student 5	25%	75%	20%	40%	75%
Student 9	0%	50%	60%	37%	63%
Student 11	50%	0%	60%	37%	63%

Explanations were provided by the students' statements during think-aloud sessions and interviews.

Some students turned their attention to the sub-micro support only after noticing changes in the applet while they were adjusting the stoichiometric coefficients. However, they did not use the models for balancing equations.

*"... , it always appeared there. I looked at it, saw it was there. Hmm, that's the molecule."* (S2)

*"I know I was surprised that something changed and something new appeared there, so I looked at it."* (S7)

Only three respondents utilized sub-micro models for more than 5% of the time in balancing equations for at least one of the equations. For two of them, based on the description of their process and eye-tracking records, these were situations where the respondents did not know how to proceed with balancing equations based solely on symbolic notation and tried to find help in the area with models. It was observed that students recalculated the models. They tended to rely on sub-micro support when they were unable to figure out the equation based solely on the symbolic level of representation. Subsequent interviews revealed that in neither case were these two respondents able to arrive at the correct solution based on the sub-micro support.

*"Hmm, I had to consciously look at them [note: models], but I didn't deduce anything from it [note: models]. Just like: it doesn't equal, well. But I see that here too. I calculated within those coefficients that they are not equal. ... I really can't say to what extent watching those balls, for instance in the case of this equation, was then a result of some frustration from it not working out."* (S5)

*"Here, I was counting the balls when it didn't add up. But I knew it wasn't balanced. That I could see it from those numbers. ... Based on the principle that a drowning man will clutch at straws, I similarly attempted to calculate the models."* (S8)

The statement of another student confirms that engagement with models was sought in cases when balancing equation "traditional" way was complicated. Furthermore, it was also noted that the sub-microscopic representations did not provide help in balancing equations.

*"I tried looking at the models to see if they would help me. But I concluded that I'd rather go back to that equation." (S7)*

Based on respondents' gaze videos and RTAs, the majority of respondents did not use sub-micro support. The individual respondents' overall ratio of TFD ranged between 0.6% and 14.5% (average 2.7%), as presented in Table 3.

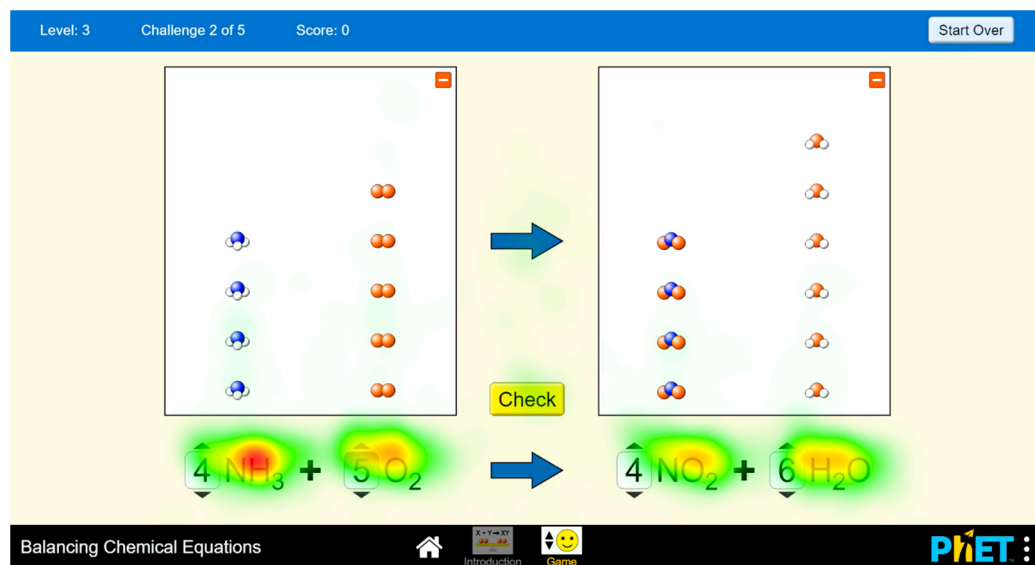
**Table 3.** Ratio of TFD when balancing individual chemical equations in applet.

	E1		E2		E3		E4		Overall Ratio of TFD
	Ratio of TFD	Score	Ratio of TFD	Score	Ratio of TFD	Score	Ratio of TFD	Score	
Student 1	3.3%	2	0.7%	2	1.2%	2	0.7%	2	1.3%
Student 2	2.2%	2	0%	2	0.3%	2	0.7%	2	0.6%
Student 3	7.0%	2	0%	2	1.3%	2	1.1%	2	1.5%
Student 4	4.2%	2	1.4%	1	0.6%	1	0.4%	2	1.0%
Student 5	5.3%	2	2.5%	2	8.1%	0	6.2%	2	7.0%
Student 6	3.2%	2	1.6%	2	0.1%	2	0.5%	2	0.8%
Student 7	3.4%	2	1.5%	2	0.5%	1	0.3%	2	0.8%
Student 8	21.7%	0	5.4%	2	0.5%	2	20.3%	0	14.5%
Student 9	0.8%	1	0.6%	2	6.8%	0	0.5%	2	1.9%
Student 10	0.5%	2	0.7%	2	0.2%	2	0%	2	0.3%
Student 11	0.5%	1	0.0%	2	0.7%	0	0%	2	0.4%
Average ratio of TFD	4.7%		1.30%		1.80%		2.80%		2.74%

The heatmaps in Figures 6 and 7 allow for the comparison of different uses of the applet environment by two respondents in balancing an equation at level 3 in the main part. Figure 6 shows the resulting heatmap of a respondent who used sub-micro support when balancing but was unsuccessful. Meanwhile, the resulting heatmap in Figure 7 belongs to a respondent who proceeded solely based on symbolic representation and was successful. As evident from the heatmaps, in both cases, the greatest attention was paid to the symbolic notation of the equation.



**Figure 6.** Focus of respondent who used sub-micro support when balancing level 3 equation. Note: The color gradient shows level of respondent attention (fixation). Cool colors represent areas that received the least attention, whereas warm colors show long gaze duration.



**Figure 7.** Focus of respondent who used only symbolic notation when balancing level 3 equation.

#### Reasons for Non-Use of Sub-Micro Representations

From think-aloud sessions and interviews, several reasons for not utilizing or unsuccessfully utilizing sub-micro support in balancing equations within the applet were identified. Students mentioned that in their instruction on balancing equations, they had not encountered the depiction of molecules using models. They did not see significant assistance in sub-micro support for balancing equations and proceeded according to what they were accustomed to. They preferred to rely on their learned procedures and mathematical skills.

*“I preferred to proceed through the numbers. Even though math isn’t exactly my strongest subject, I still preferred to work numerically rather than rely on pictures in this case... Looking back now, those pictures, the way those molecules are depicted, don’t look bad either. Maybe I could have focused more on them as well. That I might have managed to balance the previous equation quicker. But still, numbers and paper are my favorites.”* (S3)

*“We never had any models anywhere. So, a person primarily focuses on the equation.”* (S5)

*“I tried not to look at them [note: models] because I’m not used to it, so it didn’t seem all that important or helpful to me.”* (S8)

Another reason could be a lack of understanding of the sub-micro representation. From the following statement, it is evident that the respondent was unable to distinguish the individual reacting substances from the sub-micro models.

*“Now I realize that always, the things that are increasing, the balls that are added, are above it. It’s really silly, but I didn’t get it at the moment. That here oxygen is being added, so it’s added here. Here we have ethyne, so it’s added above it. At that moment, I didn’t assess it like this at all. Just left, right.”* (S5)

Two respondents also mentioned that the applet environment, which was constantly changing, distracted them.

*“It rather distracts me, I don’t take it as help, that those balls or molecules are accumulating there.”* (S8)

Overall, from the statements, it emerges that students lacked experience from previous instruction in utilizing sub-micro level representations to be able to use them effectively in the applet environment.

#### 5.4. Students' Approach When Balancing Chemical Equations

For the analysis of the procedures for balancing chemical equations and identifying the reasons for success and failure, students were divided into three groups based on their overall weighted score in balancing chemical equations (see above): Group 1—students who balanced chemical equations without errors, Group 2—students whose balancing equations results indicate minor shortcomings, and Group 3—the least successful students.

##### 5.4.1. Group 1

Students in this group correctly balanced all chemical equations on the first attempt. Their methods suggest effective strategies for balancing equations, proceeding primarily in a systematic manner. They began by balancing one element and gradually moved on to others, revisiting previous steps during balancing, checking and, if necessary, adjusting the values of stoichiometric coefficients based on changes in the ratio of elements' atoms. Regularly checking atom ratios helps in detecting and correcting errors early. Their process also included checking the entire equation before the final evaluation. Two respondents from this group used the trial-and-error method [70] when balancing an equation at level 3 when they could not find the solution through a systematic approach. In both cases, the issue was the need to increase a coefficient value to balance odd and even numbers of atoms. Among respondents in this group, Student 10 stood out for not balancing the equation sequentially but entering final stoichiometric coefficients after calculating atom ratios in his head. This approach indicates that the respondent was able to manipulate the coefficients without the need to visually record each step of the process.

##### 5.4.2. Group 2

This group included students who needed to make at least one correction attempt, with three out of four correction attempts being successful. These students typically began the equation-balancing process by observing the ratio of elements other than oxygen and hydrogen. Respondents stated they prefer to start with elements that are exceptions in the equation. They also applied an iterative approach, repeatedly revisiting and checking their steps to verify their accuracy. However, a comprehensive check of the equation before its evaluation was not always performed. Failure to detect errors or inaccurate checks could result from inefficient ongoing and final checks or the absence of a final check. These errors might be caused by inattention, such as overlooking a subscript, failing to count an element in a molecule, or simple arithmetic errors in addition and multiplication. Balancing the disparity between odd and even numbers of element atoms in level 3 equations was problematic for students. This issue led to repeated unsuccessful attempts to find a solution, with students consistently applying the same strategy unsuccessfully, limited in their ability to use the necessary higher stoichiometric coefficients to solve the problem.

##### 5.4.3. Group 3

Group 3 included three respondents who attempted to correct two equations, with at least one of them failing to find the correct solution. They made mistakes not only in higher-difficulty-level equations but also in level 2 equations. These results suggest that respondents either lacked effective strategies for balancing chemical equations or applied them incorrectly. The procedures of students in this group were characterized as unsystematic and random. Each respondent approached the balancing of individual equations differently, without a clear and fixed procedure. The lack of regularity in checking and recalculating the atoms of elements meant that opportunities to identify and correct errors were often overlooked. In cases where checks were made, respondents were often unable to find or effectively correct the mistake. Failures in balancing equations were caused by a wide range of problems, including overlooking elements, miscounting atoms due to incorrect subscript evaluation, simple arithmetic errors, or not accounting for all molecules. These oversights led to incomplete balancing, with respondents repeatedly making the same mistakes, indicating a lack of ability to learn from previous attempts. Two respondents

experienced faltering in the equation-balancing process. The solving time of the first attempt (and an analysis of their procedure from gaze video) suggests that respondents did not perform enough steps to correctly balance the equation. An interesting aspect was that respondents did not hesitate to use higher stoichiometric coefficient values, but these coefficients were entered entirely at random, as an attempt to find a possible solution. The trial-and-error method was typical for these respondents. The analysis of these respondents' procedures revealed a significant number of causes for their failure, associated with the absence of a strategic approach to balancing chemical equations, insufficient attention, or mathematical skills.

## 6. Discussion

The findings must be contextualized within the specific demographics of our participant sample. The subjects were students who had undergone a minimum of six years of chemistry education, spanning both lower- and upper-secondary levels, and had successfully passed a chemistry matriculation exam, further choosing to pursue chemistry in their higher education. Therefore, they represent a cohort of potentially motivated individuals. Despite this, over half of these students were unable to balance chemical equations at a high-school level (see [71])—a finding consistent with prior research. Rusek, et al. [34] encountered challenges among students when solving chemical calculation problems, particularly with chemical equations, where failure was predominantly due to an inability to balance the equations properly.

### 6.1. Chemical Equations as Chemical Concepts' Intersection

The study's approach to evaluating students' ability to balance chemical equations, using methods from Hansen [59], initially failed to effectively categorize students into distinct performance groups. This outcome highlighted the fundamental limitation of pre-tests that measure procedural ability without assessing conceptual understanding. A refinement of the pre-test to focus on specific concepts related to stoichiometry, conservation of mass, and the particulate nature of substances allowed for a clearer distinction between successful and unsuccessful students.

The analysis herein focuses specifically on items from the original pre-test that directly relate to distinct chemical concepts. Whether examining students' understanding of the particulate nature of matter or their performance in areas linked to chemical equation concepts (e.g., conservation of mass, sub-micro understanding, and stoichiometry), the findings suggest that the mere ability to balance a chemical equation does not necessarily correlate with a comprehensive understanding of the underpinning concepts as a means of representing chemical reactions, and vice versa. This conclusion aligns with the findings of Holme, et al. [72], who posited that conceptual understanding and algorithmic reasoning are distinct competencies. Research indicates that the ability to balance a chemical equation does not imply proficiency in solving conceptual problems within the same thematic area (cf. [73,74]). Additionally, students' challenges in specific instances of the algebraic balancing of equations suggest the need for further research [30,75]. Conversely, while other studies indicate that the algebraic aspect of equation balancing, i.e., assigning stoichiometric coefficients, is not inherently problematic, the failure lies in understanding the concepts the equations represent [55,76,77].

This body of evidence underscores a critical gap in chemical education: the distinction between procedural proficiency in equation balancing and a deep conceptual understanding of the chemistry involved (see [18]). The implication for educators is clear: achieving a balance between teaching algorithmic skills and fostering a robust conceptual framework is essential for comprehensive chemistry education. This dual focus not only prepares students for the procedural aspects of chemistry but also ensures they grasp the underlying principles and concepts, thereby enhancing their overall competence and readiness to tackle complex chemical phenomena.

The observed moderate correlation between understanding the concept of stoichiometry and its practical application through balancing equations suggests that grasping the significance of ratios or counts of individual molecules in an equation leads to better outcomes. This is because students perceive the interconnectedness of these concepts and the application of one concept within another. From this perspective, emphasizing the importance of stoichiometric coefficients in the pedagogy of equation balancing becomes crucial. Introducing visual aids, such as scales representing the number of atoms of reactants and products, can significantly enhance understanding.

Conversely, understanding the law of conservation of mass and, even more significantly, sub-micro representations, exhibited a lower correlation. This discrepancy underscores the difference between understanding a chemistry concept and completing a school task. While from a chemical viewpoint equation balancing is an application (and in the case of sub-micro representations, a visualization), the mere school activity of the “art of balancing equations” becomes an artificial, pseudo-skill. Thus, balancing equations transforms into solving a mathematical puzzle, diluting the original disciplinary foundation (cf. [18,78–80]). From this angle, it is less pedagogically successful that, instead of fostering functional supports for understanding the meaning of chemical equations and associated concepts, artificial algorithms emerge (cf. [31,33]). These may guide students to the correct solution, but the essence of the result in expressing the course of a chemical reaction remains overshadowed.

This traditional approach might be one of the reasons behind misconceptions about the nature of chemistry tasks—it is crucial to remember the procedure, but the application of knowledge does not suffice [43]. This insight points to the need for a shift in chemistry education toward approaches that not only teach procedural skills but also deepen conceptual understanding. By doing so, educators can help students bridge the gap between performing academic tasks [31] and grasping the complex concepts that these tasks are intended to illustrate, thereby fostering a more profound and nuanced understanding of chemistry as a discipline.

### 6.2. Balancing Chemical Equations as a Problem-Solving Task

According to Goldhammer, et al. [81], the more complex a problem is, the greater the positive effect of having extended time to solve it. Balancing equations can be considered a field-specific problem-solving task, as outlined by Chiu [76]; therefore, the number of mental steps one needs to take (see [42]) to balance an equation is greater in level 3 equations compared to level 2 equations. However, this premise was confirmed in our study only for level 2 equations when considering only the time of the first attempt (i.e., without corrections). A moderate correlation between longer solution times and higher success rates was identified for level 2 equations. For level 3 equations, this correlation was inverse and of lower magnitude, which reflected some students’ difficulties with more-complicated equations that required more steps to be balanced. The positive use of time is particularly evident among the group of persistent and inefficient solvers (students 3, 4, 5, 6, and 9), who compensated for their lack of skill or proficiency in equation balancing with effort (cf. [82]).

Conversely, when considering the total time spent solving the problem, no relationship was found between the respondents’ success in balancing equations and the time required for solving. However, when focusing on the total time spent (including first and corrective attempt) balancing individual equations, a negative effect of time was found for the initial chemical equations. The more time a respondent spent balancing the initial equations at given levels of difficulty, the lower their success rate was (cf. [82]), which shows that the students are either proficient in balancing chemical equations and are capable of solving the given equation or they encounter difficulties and their efforts do not lead to a positive outcome (see also [81]). This outcome is probably affected by the smaller number of respondents included in this study.

Monitoring the students' processes also revealed insights into their "learning in direct transmission". Less time and higher success rates in balancing the second set of equations suggest increased confidence and proficiency in solving algorithms. This conclusion is supported by number of students' statements, who initially hesitated to use higher stoichiometric coefficients in the first equation at a higher level of difficulty (E3). Based on their experience with the first equation, they were able to implement the algorithm in the next equation (E4). The initial lack of success was likely due to the student's inexperience, stemming from a high-school education that emphasized a certain form of equation balancing.

This highlights the nuanced relationship between the time spent on problem-solving and learning outcomes in the context of chemical education. It suggests that while persistence and effort can compensate for initial lack of skill, there is a critical need to align instructional strategies with the development of both procedural proficiency and conceptual understanding to facilitate meaningful learning in chemistry.

The findings suggest that the tendency of some students to give up on a task or make only a brief attempt without achieving the correct result could be explained by the relationship between the anticipation of a correct outcome and the effort expended, including the time spent on a task, as noted by Payne and Duggan [83]. In the context of equation balancing—a critical aspect of chemistry education—students might perceive the problem as less likely solvable, subsequently spending less time on it (cf. [16]).

The categorization of equation difficulty was supported based on the solution time, as the level 3 equations were found to take longer to solve compared to the level 2 equations. However, significant differences in outcomes were observed among students even within the same difficulty level. This parallels findings by Niaz and Lawson [84], who identified a positive correlation between working memory capacity and success in balancing more-complex chemical equations using a trial-and-error method. Among the respondents with 100% success, two utilized this method, indicating sufficient mental capacity for the necessary steps in balancing. In contrast, the lower success rate of the least successful students using the same method could be attributed to limited working memory capacity. To confirm this hypothesis, assessing working memory capacity through pre-tests or employing methods to measure cognitive load, such as heart rate or temperature measurements, could be beneficial (cf. [85,86]).

The analysis of approaches to balancing chemical equations revealed important factors influencing student success. Students within each group (successful, average, unsuccessful) adopted similar strategies, while unsuccessful solvers often failed to convert their approach into the correct result, resorting to limiting strategies (cf. [87]). Gaze path analysis highlighted the need for a more systematic and iterative approach to balancing, emphasizing result verification. The trial-and-error method, chosen by many students, proved insufficient, essentially amounting to random attempts rather than a systematic approach, which was particularly ineffective for equations requiring higher stoichiometric coefficients.

Based on the students' approaches observed in this study, students identified as impulsive solvers failed due to their overly rapid actions, which led to overlooking parts of the equation or formulae (see [88]). This outcome stems from the previously mentioned emphasis on symbolic notation, and it can be inferred that this might not occur with the inclusion of sub-microscopic representations (see [77]). Impulsive solvers score lower [89] because they do not thoroughly plan their approach, making their success somewhat accidental [90].

Another factor impacting success was found to be both ongoing and final verification. While the group labeled as inefficient solvers attempted to verify their results, inaccuracies or an inability to find the correct solution rendered these checks unsuccessful. Inefficient solvers exhibited aspects of reflective thinking (cf. [91]), such as monitoring and determining the correctness of a solution. The connection with insufficient mathematical skills was particularly evident for equations of the highest difficulty level. Students struggled with balancing an uneven number of atoms, often leading to repeated adjustments. The

mentioned limiting strategy of hesitating to use higher stoichiometric coefficients also played a significant role. Higher coefficients require operating with larger numbers, which may have been more challenging for students. If the purpose of including equations in the chemistry curriculum is to describe real reactions, it is natural for students to encounter higher coefficients. Teachers' attempts to simplify challenging content by incorporating equations considered easy due to lower stoichiometry values are counterproductive, as this approach loses sight of the original goal.

### 6.3. Balancing Chemical Equations in the PhET Applet Environment

One of the goals of this research was to observe students' work within an applet environment. The assumption that the availability of support in the form of sub-micro representations would aid students in balancing equations (see [62]) was not confirmed. However, the analysis of their visual attention revealed that students primarily focused on symbolic representations when balancing equations. One reason for this could be the influence of textbooks, where sub-micro representations are relatively rare [26,27,92] and explained or described enough for learners [92]. Given the impact of textbooks on teaching [93,94], it can be assumed that this is how the topic is similarly presented to students in school. This then reflects in their ability to think about chemical concepts at the particulate level [95,96].

The negative correlation between equation-balancing success and the length of fixation on sub-micro representations confirms the conclusions. The detrimental effect of considering sub-microscopic representations manifested in the outcomes of unsuccessful students. While successful students likely knew an effective procedure that required only the symbolic level, less-successful students displayed a well-documented discrepancy between the ability to write equations using symbols and using sub-micro representations (cf. [30]). The focus of visual attention on sub-micro representations can be explained by the well-described effect of attempting to explore all provided options [43], which differs from successful or expert approaches. Unsuccessful students not only fail to choose effective strategies but also do not integrate additional provided information—in this case, models of the reactants and products of chemical reactions—into their understanding of the problem, or they waste time on less-relevant details. This result reaffirms the necessity of incorporating sub-micro representation into teaching for meaningful learning [62,96], which would suit the successful students and mostly the unsuccessful students. Solutions including approaches by Davidowitz, et al. [60] or Park, et al. [96], who, when presenting chemical concepts, emphasize the sub-microscopic structure and aim to affect multiple representations, exemplify how to promote this topic's instruction.

When it comes to balancing chemical equations, the results showed that, when solving a mathematical equation, students proceed through a trial-and-error method. The more successful ones tend to estimate the ratios of the compounds correctly and avoid making mistakes, or they find the correct coefficient ratios more quickly. In the group of students who need more time, the step-by-step approach takes longer and/or leads to errors.

This research thus indicates that despite efforts to offer students scaffolding in the form of an applet environment, students found the applet confusing, as also reflected in the conducted interviews. Displaying sub-micro representations during equation balancing tended to fragment their attention. The expectation of student engagement with a new environment featuring new elements of representation was largely unmet. For a more effective use of the applet environment, it is essential to first connect students' symbolic and sub-microscopic conceptions of reaction processes.

## 7. Limitations

The study's methodology encompasses a deliberate selection from an available pool of students and an in-depth examination of eleven participants. This restriction, albeit seemingly constraining, facilitated a dual-purpose approach: it enabled the collection of more extensive data on the initial cohort, comprised predominantly of future chemistry teachers.

This particular demographic represents a segment potentially more motivated due to their comprehensive exposure to chemical education across both lower- and upper-secondary levels, including the accomplishment of a chemistry school-leaving exam. Consequently, these participants have engaged with the subject matter in the recent past, allowing our results to reflect the current situation without the adverse impact of memory degradation. The smaller sample size within the eye-tracking study is reflective of typical participant numbers in such research, providing a unique advantage. This not only allowed for the assessment of test scores but also facilitated the observation of eye movements, the conducting of think-aloud protocols, and the execution of interviews, offering a multifaceted view of the cognitive processes involved.

A notable limitation was the pre-test's insufficiency in distinguishing among students for selection purposes, as initially intended. Despite this, the eye-tracking study successfully captured a range of student approaches, categorizing them as successful, average, and unsuccessful. This diversity in methodology highlights the complexity of learning processes and the varied strategies students employ.

Another significant challenge was the introduction of an applet designed to assist students in equation balancing, which, contrary to expectations, led to confusion. Students accustomed to solving equations on paper found the digital interface counterintuitive. The original hypothesis based on previous studies using this applet (Carpenter 2016, Hansen)—that additional displayed information (representations) would be beneficial—was not confirmed, suggesting a potential misalignment between digital instructional tools and traditional learning habits.

Finally, the results are derived from students balancing just four chemical equations. Although utilizing a greater number of equations could potentially provide additional insights, this limited selection was intentionally chosen to avoid overwhelming the students. Furthermore, the students demonstrated a consistent pattern in their responses to the two pairs of equations, suggesting that including more equations of comparable complexity (in terms of the number of reactants and products) would unlikely alter the observed trend.

## 8. Conclusions

This study provides significant insights into the complex domain of learning and teaching chemical equations, underscoring the intricacies of aligning instructional methods with students' cognitive processes and the inherent challenges therein. The investigation into students' approaches to balancing chemical equations, especially within the digital applet environment, has highlighted several critical aspects of chemical education. Firstly, it was surprising to find that some students, even after completing upper-secondary-school chemistry, struggle with balancing even simple chemical equations. It becomes evident that students' proficiency in balancing chemical equations cannot be viewed solely through the lens of their ability to manipulate symbolic representations. This study therefore reaffirms the enduring relevance of Johnstone's triplet in chemical education.

Secondly, the observation that students often rely on learned algorithms, which merely replicate the initial depiction of the chemical reaction, including ratios of reactants and products, suggests that this learning outcome is treated more as an isolated "school-chemistry skill" rather than a true reflection of their understanding of fundamental chemical processes. The reasons behind students' success included the lack of a systematic approach (using the trial-and-error method), insufficient revisiting and checking of their steps, absence of a final check, overlooking elements or subscripts, simple arithmetic errors (in addition, multiplication), and hesitation to use higher stoichiometric coefficients.

Furthermore, students' tendency to focus primarily on symbolic representations at the expense of integrating sub-microscopic representations into their problem-solving strategies points to a potential disconnect in the way chemical concepts are taught. The reliance on symbolic representations may limit students' ability to conceptualize chemical reactions at the particulate level. This limitation not only affects their performance in tasks

like equation balancing but may also hinder their overall comprehension of chemistry reactions.

The negative correlation between success in equation balancing and the length of fixation on sub-micro representations within the applet environment underscores the necessity of more effective instructional designs. These designs should not only incorporate multiple representations but also guide students in making meaningful connections between them. The finding that some students found the applet environment confusing or distracting highlights the importance of the careful integration of digital tools into the chemistry curriculum. Digital tools should complement, not complicate, the learning process and should be used in a manner that enhances students' understanding of chemical concepts across all representational levels.

It is evident that it is crucial to shift the pedagogical focus from merely balancing equations to fostering a comprehensive understanding of the mechanisms underlying chemical reactions and their broader implications, which represent the true objectives of chemistry education. This approach should include the development of curricular materials and teaching strategies that emphasize the interconnectedness of macroscopic, sub-microscopic, and symbolic representations. Furthermore, educators need to be mindful of the potential pitfalls of overreliance on any single representation and strive to cultivate a balanced understanding among their students.

The timing of this study, conducted at the onset of the students' first year in chemistry teaching programs, contributes valuable insights into the preparedness of students for university-level chemistry studies. It suggests a gap between the expected and actual levels of readiness, which is critical for curriculum developers and educators to address. The diverse backgrounds of the students, stemming from various regions and schools, hint at a broader issue of inconsistency in chemistry education quality at the upper-secondary level.

These observations suggest a pressing need for systemic changes in both secondary and tertiary chemistry education to ensure a smoother transition for students and better equip them for the rigors of higher-level chemistry studies. Collaboration between secondary schools and universities could foster a more cohesive educational pathway, enhancing student outcomes and readiness for advanced scientific studies.

#### Implications for Practice:

1. **Integrated Instructional Designs:** To design instructional materials that seamlessly integrate macroscopic, sub-microscopic, and symbolic representations to help students make meaningful connections between different levels of understanding to chemical reactions.
2. **Curriculum Development:** To develop curricular materials that emphasize the interconnectedness of different representations of chemical concepts and ensure that these materials foster a comprehensive understanding of chemical processes rather than treating skills like equation balancing as isolated tasks.
3. **Teacher Training:** To provide professional development opportunities for teachers to help them understand and implement instructional strategies that integrate multiple representations of chemical concepts and to emphasize the importance of moving beyond algorithmic approaches to fostering deep conceptual understanding.
4. **Use of Digital Tools:** To carefully integrate digital tools into the chemistry curriculum in a way that complements and enhances traditional teaching methods and to ensure that these tools are used to support students' understanding across all representational levels without causing confusion or distraction.

By implementing these practices, educators can better align instructional methods with students' cognitive processes, ultimately leading to improved learning outcomes in chemistry education.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/educsci14060570/s1>. Supplementary S1: Particulate nature of matter (PNM) test, correct answers are underlined. Supplementary S2: Representational competency test. Supplementary S3: Equations balanced by students when using PhET applet.

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