



Evaluating the effect of custom developed dynamic simulations as a tool to improve students conceptual understanding of chemical equilibrium

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Abstract

The study evaluated the role of custom-developed dynamic simulations on students conceptual understanding of chemical equilibrium. An ANCOVA analysis showed posttest scores were significantly higher for the experimental group (Mpost. = 7.27, SDpost = 1.387) relative to the control group (Mpost. = 2.67, SDpost = 1.371) after adjusting for pretest scores: $F(1,24) = 71.82$, $MSE = 1.497$, $p = 0.03$, $\eta_p^2 = 0.75$, $d = 3.33$. Cohen's d was converted to an attenuated effect size d^* . The adjusted (for pretest scores) group mean difference estimate without measure error correction for the posttest scores and the pretest scores was 4.2 with a Cohen's $d = 3.04$. Alternatively, the adjusted (for pretest scores) group mean difference estimate with measurement error correction only for the posttest scores with measurement error correction was 4.23 with Cohen's $d = 3.07$. Effect size indicates a positive correlation between the intervention and students' conceptual understanding.

Keywords: chemical equilibrium misconceptions, dynamic simulations, chemical concepts, conceptual understanding, le chatelier's principle

Introduction

Learning chemical equilibrium or any chemical concept involves an understanding of chemical phenomena at three levels: (a) the microscopic, (b) the microscopic, and (c) the symbolic (Johnstone, 1993) ^[19]. Learners generally do not develop conceptual issues pertaining to chemical reactions at the macroscopic level but develop difficulty while transitioning from the macroscopic to microscopic and symbolic representations of chemical reactions, as these levels are abstract. While solving mathematical problems might strengthen students' understanding at the symbolic level, it does not necessarily or automatically help them understand chemistry at the microscopic level. According to Johnstone (1993) ^[19], an expert practicing chemistry can maneuver through all three levels with significant fluidity, whereas students who have difficulty generating connections between the three levels may experience a cognitive overload in their working memory. Chemistry instruction in secondary or post-secondary coursework generally focuses predominantly on the macroscopic and the symbolic levels. Comprehension at these two levels does not automatically allow for comprehension at the microscopic level among students, nor does it develop a student's ability to transition between the three levels like an expert does (Nurrenbern & Pickering, 1987; Nakhleh, 1993) ^[25]. Bunce *et al.* (1991), through their review of chemistry problem solving research, found that students used a Rolodex approach. According to the rolodex approach, students searched through memorized formulas in their mental schemas until they found one where the units in the data matched the units in the problem. Solving chemistry problems in such a manner suggests students focus their attention on symbolic representations rather than developing a conceptual understanding that integrates symbolic and microscopic representations. Phelps (1996) ^[28] suggested that a lack of problem-solving discontinuity is perpetuated in physical science courses because instructors allow students to disguise their lack of understanding behind

numerically correct answers. The preconception about equilibrium stems from the notion of how the idea of equilibrium is used in everyday life, where equilibrium means equality of two sides, stability, and static in nature (Schafer, 1984). While systems that reach chemical equilibrium may appear macroscopically static, microscopically the system is dynamic because of molecular movement.

Hackling and Garnett (1985) ^[14] were among the earliest researchers who studied student misconceptions about chemical equilibrium. They grouped student misconceptions about chemical equilibrium into seven broad categories. They are a) approach to equilibrium, b) characteristics of equilibrium, c) adjusting equilibrium conditions, d) effects of reaction rate, e) rate of a reaction when equilibrium is being re-established, f) equilibrium constant, and g) effect of catalyst.

Huddle and Pillay (1996) ^[17] studied chemical equilibrium misconceptions among students. Students were unable to distinguish between the rate and extent of a reaction. There are two ways that an equilibrium reaction can go. Reactants are discussed in terms of the reverse reaction rate, whereas products are discussed in terms of the forward reaction rate. According to the students' assumptions, the forward reaction and the reverse reaction happened at varying rates after equilibrium. In addition, students think that the amounts of reactant and product are equal (Demirciolu *et al.*, 2013; Heeg *et al.*, 2020; Jusniar, Effendy, Budiasih, & Sutrisno, 2020; Üce & Ceyhan, 2019) ^[16, 21, 34].

Omilani *et al.* (2020) ^[26] examined alternate conceptions of chemical equilibrium among secondary school students in Nigeria. The findings showed that students generally hold misconceptions in areas such as a) the addition of catalyst, b) the equilibrium constant (K), c) heterogenous equilibrium, d) the approach to chemical equilibrium, and e) the erroneous application of Le Chatelier's principle. Previous studies also noted misconceptions about temperature changes and reaction enthalpies. Enthalpy's role

in the reaction equation and system temperature were not understood by the students (Indriani, Suryadharma, & Yahmin, 2017) ^[18]. Any temperature changes that might have an effect on the distribution of the product and reactant molecules were disregarded by the students (Ganasen & Shamuganathan, 2017; Siswaningsih, Nahadi, & Widasmara, 2019; Yan & Subramaniam, 2018) ^[11, 32, 40]. Previous research on changes in the equilibrium constant revealed misconceptions. Students assume that changes in volume, pressure, and concentration of the reactants or products will impact the shift in equilibrium (Ganasen & Shamuganathan, 2017; Ozmen, 2008; Siswaningsih *et al.*, 2019; Uce *et al.*, 2019) ^[11, 32]. Misconceptions frequently arise when a catalyst is added to an equilibrium system. The concentration of the product or reactant will change once a catalyst is added to the equilibrium system. The addition of catalyst affects rates of both forward and reverse reactions equally (Al-Balushi *et al.*, 2012; Ganasen & Shamuganathan, 2017; Heeg *et al.*, 2020; Jusniar *et al.*, 2020; Özmen, 2008; Siswaningsih *et al.*, 2019; Üce & Ceyhan, 2019; Voska & Heikkinen, 2000) ^[1, 11, 16, 21, 27, 32, 34, 36]. Despite constant solid concentration, research shows that students believe Le Chatelier's principle can be used to describe any system, including those in heterogeneous equilibrium (Banerjee, 1991; Heeg *et al.*, 2020; Kousathana & Tsapalis, 2002; Yan & Subramaniam, 2018) ^[2, 16, 21]. A common misconception is that the addition of solids on the reactant side will cause the equilibrium to shift in favor of more products (Banerjee, 1991; Jusniar *et al.*, 2020; Kousathana & Tsapalis, 2002; Kurniawan *et al.*, 2020) ^[2, 21, 22]. Students frequently overlook the heterogeneous equilibrium system and the concentration of added substances (Heeg *et al.*, 2020; Indriani *et al.*, 2017) ^[16, 18].

Visualization and multimedia learning

As identified by the research studies above, a major reason behind students' difficulty with chemistry concepts, in particular chemical equilibrium, is that they hold a static model. Therefore, a multimedia tool that can integrate text, videos, graphs, etc. to represent a chemical reaction can significantly alleviate the conceptual difficulty experienced by students. Jones and Berger (1995) ^[20], through an empirical study on the use of digital media in a science class, determined that a combination of videos and animations were helpful to students learning the concepts of light, energy, and molecules. Schank and Kozma (2002) ^[30], in an empirical study, used ChemSense as a digital platform to teach a module on solubility. During the study, students were expected to create drawings and animations. Students demonstrated greater representational competence and an in-depth understanding of geometrical aspects of chemical phenomena in their animations. Wu and Shah (2004) ^[39] suggested five design principles a creator must consider while developing a visualization tool. They are a) offering multiple representations; b) connecting visual and conceptual components; c) providing a dynamic representation of chemical phenomena. d) allocating room for transformation between 2D and 3D structures; and e) reducing cognitive load.

While several theories (Sweller, 1994; Mayer, 2002; Van Merriënboer & Kester, 2006) ^[35] exist on addressing the effect of multimedia learning on students cognitive capacity, Schnotz's integrated model of text and picture comprehension (IMPTC) was used as the multimedia framework to guide the study. In sharp contrast to other

multimedia theories on cognitive capacity, the IMPTC model also includes two additional levels: a cognitive level and a perceptual level. The cognitive level comprises a verbal and pictorial channel, while the perceptual level consists of multiple sensory channels (Schnotz, 2005) ^[31]. A primary role of the perceptual level is to transfer information from an incoming stimulus to the working memory through sensory registers. The cognitive level focuses on processing information in the working memory and transferring it to the long-term memory for access later (Schnotz, 2005) ^[31]. IMPTC proposes that only a single mental model be constructed that integrates information from multiple stimuli (Schnotz, 2005) ^[31]. In addition, the IMPTC model assumes that pictorial information is not only sensed through the visual modality but also through other sensory modalities such as sound images (Schnotz, 2005) ^[31]. The following positive effects can be obtained using sound images: They are a) coherence and contiguity, b) modality, c) sequencing, d) related ability and prior knowledge, e) redundancy, f) structure mapping, g) deep versus superficial learning, and h) cognitive economy (Schnotz, 2005) ^[31]. The ability to visualize chemical phenomena at the atomic and molecular level is critical to developing a conceptual understanding of chemistry concepts.

According to Gupta *et al.* (2012) ^[13], effective use of digital instructional technology not only provides a productive platform for learning but can provide an educator with tools to bridge the gap between conventional and contemporary educational requirements and the overall development of a learner. Sanger (2008, 2009) reviewed empirical studies on the application of computer animations in a chemistry course. Results highlight the following key ideas: They are: (a) a student's conceptual understanding and performance improved on examinations; (b) in contrast to didactic instruction, students who used computer animations to learn chemistry concepts at the microscopic level had fewer misconceptions; and (c) in contrast to static images conventionally seen in power point presentations during lectures or in textbooks, students who explored concepts using computer animations understood ideas at the microscopic, macroscopic, and symbolic levels. Yeziarski and Birk (2006) ^[41] examined how computer animations can alleviate students' misconceptions about the particulate nature of matter. Results of the study indicated that animations at the atomic and molecular level enabled students to develop better mental models of particle properties and behaviors. The process of conceptual change is an ongoing challenge among members of the chemical education community or the broader educational community. Computer simulations and animations can facilitate the process of conceptual change by highlighting students' misconceptions and presenting plausible scientific conceptions. Empirical studies by (Gorsky and Finegold 1992; Tao and Gunstone 1999; Trundle and Bell, 2008) ^[12, 33, 3] highlight the idea that interactive computer-based laboratory simulations can enable learners to confront their beliefs and experience discrepant events preselected by the program. Simulations have been widely used in chemistry education. Interactive simulations can offer dynamic access to various levels of representation, making objects visible that the human eye could not directly see (Ganasen & Shamuganathan, 2017; Moore, Chamberlain, Parson & Perkins, 2014; Watson, Dubrovskiy & Peters, 2020) ^[11, 23, 37].

Conceptual framework

Brown & Hammer's (2008) complex systems theory served as the conceptual framework for the study. Chemical equilibrium is a dynamic process, i.e., altering a variable can have a significant effect on other variables in the system during a chemical reaction. Hence, a theory that incorporates a system's approach will be considered for the study. According to complex system theory by Brown and Hammer (2008), a system is one in which several components interact with one another. A change happening in one part of the system can influence another variable in the system, which in turn can affect the initial component of the system where the change was induced. Students not only hold misconceptions but also hold an algorithmic view while solving chemical equilibrium problems. Students use LeChatelier's principle (LCP) in an algorithmic manner while determining equilibrium shifts without developing a conceptual understanding. The four key components that make up complex systems are intrinsic dynamism, non-linearity, emergent structures, and embeddedness. The simulations were carefully constructed, with elements of system theory woven throughout.

Methodology

The researcher met participants in-person during class and explained the details of the study after getting permission from the course instructor. Additionally, participants were briefed about the institutional review board (IRB) protocol. Participants in the experimental study were recruited from three sections of the General Chemistry II course. At the end of a two-week period, 27 students had signed up to participate in the study. The 27 students were then randomly assigned to the control and experimental groups. Participants in the control and experimental groups met over two days to complete the study. During visit 1, participants completed the pre-test. The pre-test was finished by each student in about 15 minutes on average. The post-test took each student, on average, about 15 minutes to finish. During the second session, participants in the experimental group completed the intervention. Following a 30-minute break after intervention, participants completed the post quantitative assessment. The intervention lasted around 90-110 minutes.

To find common misconceptions among students, the Chemical Equilibrium Misconception Test (CEMT) was created. The quantitative instrument consisted of a total of 11 items. The instrument was developed based on chemical equilibrium misconceptions reported in the literature (Hackling & Garnett, 1985; Hameed *et al.*, 1993) [14, 15]. The instrument will be available on request. A pre/posttest design was used for data collection. During the pre- and post-quantitative phases of the pilot study, student feedback was obtained to improve the quality of the instrument. During the pre-quantitative phase, students completed the chemical equilibrium misconceptions test (CEMT). Following an intervention and a brief recess, participants completed the post-quantitative test.

Instrument reliability

The quantitative data from the CEMT test, pre- (control and experimental), and post- (control and experimental), were subjected to a Kuder-Richardson (KR-20) analysis to determine reliability. KR-20 analysis of the CEMT instrument is shown in Table 1.

Table 1: KR-20 Reliability Analysis

		N	%
Cases	Valid	27	100.0
	Excluded ^a	0	.0
	Total	27	100.0

a. Listwise deletion based on all variables in the procedure.

Cronbach's alpha	Number of items
0.708	11

	Intraclass correlation ^b	95% Confidence interval F test with true value 0					
		Lower bound	Upper bound	Value	df1	df2	Sig
Single measures	0.181 ^a	0.088	0.336	3.428	26	260	.000
Average measure	0.708 ^c	0.513	0.848	3.428	26	260	.000

- The estimator is the same, whether the interaction effect is present or not.
- Type c interclass coefficients using a consistency definition. The between measure variance is excluded from the denominator variance.
- This estimate is computed assuming the interaction effect is absent because it is not.

Content validity

A group of seven experts completed the instrument's content validity. On a scale of 1-4, experts were asked to rate the test's items. The criteria set forth to evaluate the CEMT's content validity were as follows: a) item level of representativeness in measuring the aligned overarching construct (4 being the most representative); b) item importance in measuring the aligned overarching construct (4 being the most essential); and c) item level of clarity (4 being the clearest). Additionally, written comments from experts were obtained. The CEMT's piloting was done to ensure that the reading level was appropriate for college students. The 27 students were instructed to circle any terminology that they did not understand.

The content validation index (CVI) was calculated. The relevance rating was recorded as either 1 or 0, where 1 represents the relevance scale of 3 and 4, and 0 represents the relevance scale of 1 and 2. The I-CVI was calculated by dividing the total number of experts by the number of experts who gave a rating of 3 or 4. For instance, an item with an I-CVI of 0.80 is rated 3 or 4 by four out of five experts. Polit and Beck (2006) [29] state that a CVI value of 1 is appropriate for groups of three to five experts.

Researchers frequently use CVI to assess content validity. However, it does not take into account the potential for inflated values due to chance agreements. Because it eliminates any random chance agreement, the computation of the Kappa coefficient ensures a better understanding of content validity. The probability of chance agreement must be calculated in order to compute the Kappa statistic, which is $P_c = [N! / A! (N - A)!] 0.5N$. In this equation, N is the total number of experts on the panel, and A is the total number of experts who concur that the topic is important. The resulting formula for the kappa statistic is $K = (I-CVI - P_c) / (1 - P_c)$. According to the Kappa evaluation criteria (Polit & Beck, 2006; Zamanzadeh *et al.*, 2014) [29, 42] values above 0.74, between 0.6 and 0.74, and between 0.4 and 0.59 are regarded as excellent, good, and fair, respectively. Table

2 presents the content validity analysis of items in the CEMT.

One item had a Kappa value of 0.6, which was regarded as a good item, and another had a Kappa value of 0.44, which

was regarded as a fair item. Nine out of the eleven items had Kappa values above 0.74, which was 1.00. This indicates that the test had good content-related validity, measuring one factor, chemical equilibrium misconceptions.

Table 2: Conditional validity measurement

Items	E1	E2	E3	E4	E5	E6	E7	# of expert agreement	ICVI	Pc	K	A	A!	(N-A)!
1	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
2	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
3	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
4	0	1	1	1	0	1	1	5	0.71	0.1641	0.66	5	120	2
5	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
6	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
7	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
8	0	1	0	1	1	0	1	4	0.57	0.2734	0.41	4	24	6
9	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
10	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1
11	1	1	1	1	1	1	1	7	1	0.0078	1	7	5040	1

N = 7; N! = 5040; E1-E7 corresponds to experts 1-7, pc -probability of chance agreement; K = kappa statistic.

Intervention

Intervention was provided in the form of custom developed computer simulations. The intervention on average lasted about an hour. Participants in the control group were allowed to use lecture notes on the topic of chemical equilibrium. During the first session, students were given the pre-test. On average it took around 20 minutes for the participants to complete the pre-test on CEMT. During the second session, participants in the experimental group completed the intervention. Following a 30-minute break after intervention, participants completed the post quantitative assessment. The intervention lasted around 90-110 minutes.

Computer simulations

The simulations used in the study were custom developed by the author using SCRATCH® program developed at the Massachusetts Institute of Technology (MIT), Cambridge, MA. The 12 simulations used in the study had an audio component that was seamlessly blended with the visual component.

Chemical reactions typically occur within a single system and involve reactants and products, so the idea of a separated two-piston system (reactants and products) may be controversial. It was a conscious decision to design the two-piston system. This design was made in part to show students how reactions can still happen in forward and reverse directions even after a system has reached equilibrium. In other words, even after a system reaches equilibrium, reactants and products continue to form. The two arrows in a reaction representing chemical equilibrium are modeled by the tunnel separating the two piston systems. The narrator will read a disclaimer before each simulation begins. The disclaimer informs users of the logic behind the two-piston system design. Students are therefore aware that a chemical reaction or reactions only take place in one system. In lieu of spaces, only representative figures of simulations are shown below.

The following buttons were present in every simulation: start, stop, reset, play, pause, and mute. Although there is a mute button, it is strongly advised that students not use it. The 12 simulations' goals and the concept upon which they were based are listed in Table 3 respectively.



Table 3: Simulation sequence

Simulation #	Concept	Notes
1	Concept of chemical equilibrium	Macroscopic view of the system
2	Concept of chemical equilibrium	Microscopic view of the system
3	System at equilibrium	A system that's attained dynamic equilibrium
4	Concentration and particle mode	Change in concentration & graphical representation of concentration vs time
5	Rate and particle mode	Change in concentration & graphical representation of rate of the reaction
6	Two body pulley experiment	An analogy model demonstration equilibrium constant K
7	Effect of concentration	Microscopic view of concentration change
8	Effect of concentration	Change in concentration & graphical representation of concentration vs time
9	Effect of concentration	Change in concentration & graphical representation of rate of the reaction
10	Effect of volume	Microscopic view of concentration change
11	Effect of volume	Change in concentration & graphical representation of concentration vs time
12	Effect of volume	Change in concentration & graphical representation of rate of the reaction

Simulation # 1 presents a macroscopic view of the system attaining chemical equilibrium. In the case of the system shown in equation 1, nitric oxide (NO) is a colorless gas and chlorine (Cl₂) is a yellow-colored gas. The product nitrosyl chloride (NOCl) is a light, yellow-colored gas. Participants can observe how the reaction continues to occur in either direction after the system has attained equilibrium. Figure 2 shows the purpose of the lens option. The lens on and off

buttons allowed participants to peek through the macroscopic system into the microscopic level. The goal of simulation #2 (Figure 1) is to help students comprehend that although systems that reach chemical equilibrium may appear macroscopically stable and static, the system is dynamic at the microscopic level due to both molecular movement and the ongoing process of bond creation and breakage. Simulation #3 represents a system that's attained dynamic equilibrium in microscopic mode.

In addition to showing a system reaching chemical equilibrium from a particle perspective, simulations #4 (Figure 2) and #5 (Figure 3) also showed concentration as a function of time and the rate of the reaction, respectively. An analogy model was presented in Simulation #6. The idea of an equilibrium constant was explored using a traditional two-body pulley experiment on an inclined ramp. Participants in the post-interviews stated that simulation #6 was their favorite out of all the simulations because it made the idea of the equilibrium constant simple to understand.

There were two components to Simulation #7. The simulation will begin with a system reaching chemical equilibrium being displayed in particle mode. In the simulation's second phase, participants can perturb an equilibrium system by raising the level of nitric oxide (NO), then watch what happens when the system returns to equilibrium. Like simulation #7 are simulations #8 (Figure 4) and #9. The only distinction between simulations #8 and #9

Simulation #10 was split into two parts. The simulation will begin with a system reaching chemical equilibrium being displayed in particle mode. In the second phase of the simulation, participants can perturb an equilibrium system by reducing its volume and watch what happens when the system reaches equilibrium again. Simulation #10 is comparable to simulations #11 and #12. The only distinction between simulations #11 and #12 was that simulation #11 showed changes in concentration as a function of time, while simulation #12 showed changes in reaction rate.

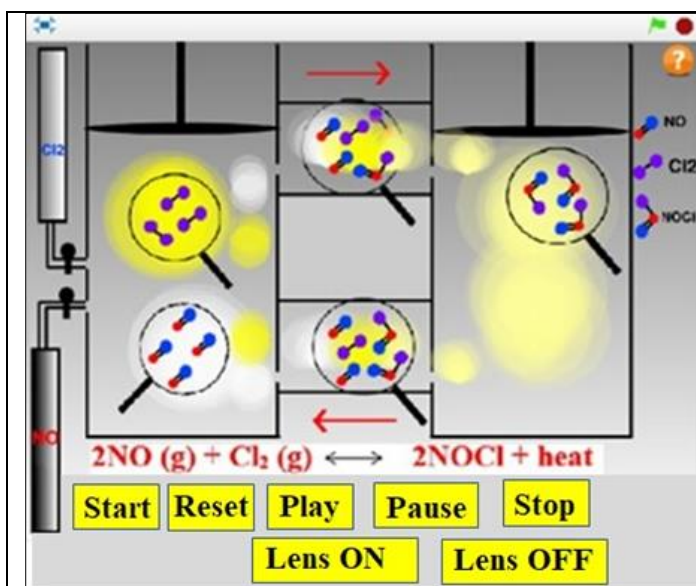


Fig 1: Microscopic view of the system using the lens option (Simulation # 2)

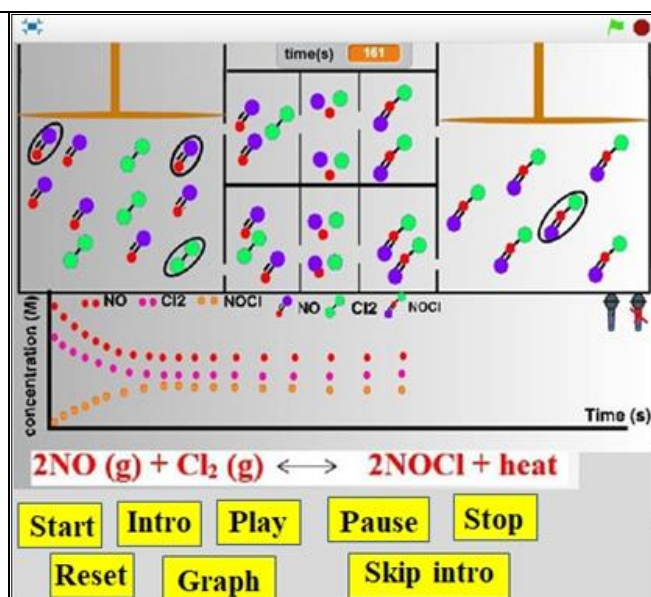


Fig 2: Concentration versus time (Simulation # 4)

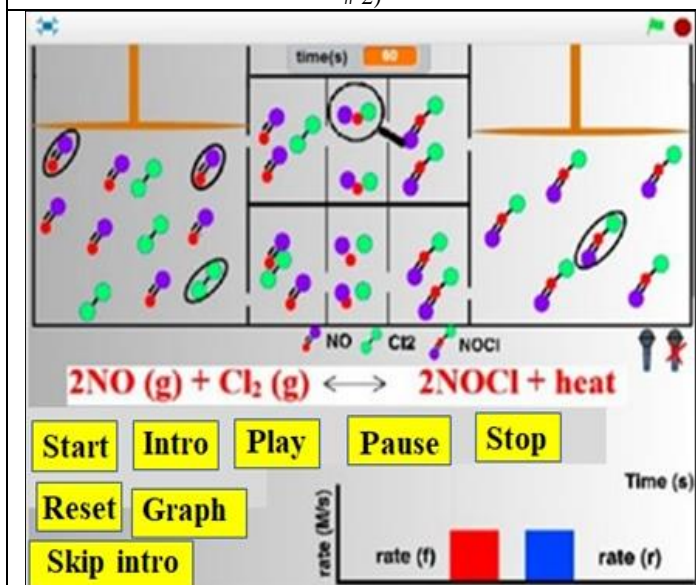


Fig 3: Rate versus time (Simulation # 5)

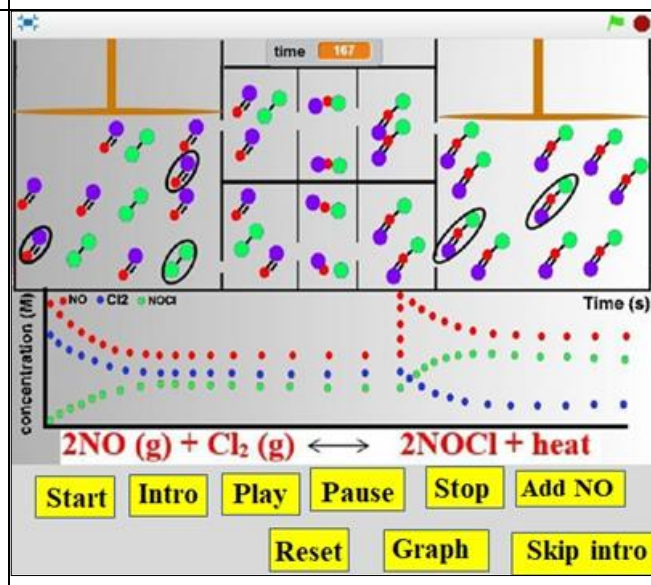


Fig 4: Effect of addition of NO (Concentration vs time) (Simulation # 8)

Results

Pre-quantitative test data analysis

When it came to items 1 (27%, 42%), 3, (27%, 33%), 5, (40%, 50%), 8, (87%, 25%), and 10, (60%, 25%), a higher percentage of students shared the common misconceptions mentioned in the literature. The most prevalent chemical equilibrium misconception, according to the literature, is that students believe reactant and product concentrations are equal at equilibrium (items 3 and 5). The larger theme, properties of chemical equilibrium, is expressed by items 3 and 5. The idea used in everyday life that equilibrium means equality of two sides, stability, and being static in nature is the source of the preconception of equilibrium. Systems that reach chemical equilibrium may appear macroscopically stable and static, but when viewed from a microscopical perspective, the system is dynamic due to both molecular movement and the ongoing process of bond creation and breakage. Applying macroscopic characteristics to the microscopic level results in a misunderstanding of chemical equilibrium, according to Gussarsky and Gorodetsky (1990).

A group of students also believed—based on their justification of the equilibrium constant (K)—that the concentrations of the reactants and products are equal at equilibrium. The ratio of the concentration of the products to the concentration of the reactants is used to calculate the equilibrium constant (K). A system is at equilibrium when $K = 1$, which is a concept that is frequently reinforced in textbooks or in classroom instruction. Although $K = 1$ indicates a system is in equilibrium, it does not imply that the ratio of the concentration of the products to the reactants is equal. In other words, $K=1$ is just a figurative representation of an equilibrium system. On the other hand, students who believed $K=1$ to be more than just a symbol held the opinion that $K=1$ implies that the numerator and denominator must be equal. As a result, at equilibrium, the concentrations of the reactants and products must be equal.

The misconception that the concentration of NO and NOCl at equilibrium must be equal because they coexisted in a 2:2 stoichiometry was held by 50% of students in the control group and 40% of students in the experimental group who responded to item #5. According to Bilgin (2002) [5], students memorize the rules they are taught and attempt to apply them without fully understanding them. Consideration of co-efficient in a chemical reaction was found to be the root of the misconception, particularly for item 5.

Le Chatelier's and stoichiometric principles were incorrectly applied by 40% of students in the control group and 33% of students in the experimental group when solving item 8. When the concentration of NO is increased at equilibrium, item 8 asks students to predict whether the equilibrium constant will remain the same, go up, or go down. In other words, NO is a reactant, and adding reactants to a system at equilibrium will change the equilibrium constant of a reaction. Participants generally agreed that as more NO is added to the system, the reaction will shift to the right because there are fewer moles on the right side, which will result in an increase in NOCl concentration and a decrease in NO and Cl₂ concentration. Similar results were reported by Hackling and Garnett (1985) [14] and Hameed *et al.* (1994) in their respective studies.

For item 9, 33% of control group students and 47% of control group students agreed with the widespread misconception that when a system's equilibrium is disturbed

by a reduction in volume, the forward reaction rate rises and the reverse reaction rate falls. Hackling and Garnett (1985) [14] proposed a potential explanation for this misunderstanding. Students' false belief that reaction rates changed to facilitate predictions made using Le Chatelier's principle (LCP) led to the misconception.

Items 6, 9, and 11 are those for which students demonstrated a higher percentage of additional misconceptions. When responding to item 6, 33% of participants in both groups believed that the equilibrium constant K would be less than 1. 20% of students in the experimental group and 25% of students in the control group disagreed with the statement in item 9 that the rate of reverse reaction decreases as the system volume is reduced. Most students, according to Hackling and Garnett's research (1985) [14], had a qualitative understanding of how reactant and product concentrations changed as the reaction drew nearer to equilibrium.

Item 11 is a prime example of how Le Chatelier's principle has been incorrectly applied. The misconception that when volume is reduced to a system at equilibrium, when equilibrium is re-established, the concentration of NOCl will be less and the concentration of Cl₂ will be greater than the initial equilibrium was held by 42% of students in the control group and 67% of students in the experimental group. For this reason, Cheung (2009) [8] asserts that students are frequently expected to predict the direction of an equilibrium shift during classroom discussions of chemical equilibrium involving LCP. The majority of textbooks even include a table showing the direction of an LCP-based equilibrium shift when an equilibrium system is changed. The consequences of the system regaining equilibrium are not emphasized during instruction.

A higher percentage of students correctly responded to items 3, 4, 5, and 8.

Post-quantitative test data analysis

For item 1, the common misconception that the rate of the forward and reverse reactions stays the same as the system approaches equilibrium was held by 42% of participants in the control group and 7% of participants in the experimental group. The proportion of participants in the control group has remained constant, but the proportion of participants in the experimental group holding misconceptions has decreased from 27% to 7%.

For item 3, 33% of students in the control group and 7% of students in the experimental group still believed that the concentrations of reactants and products are equal at equilibrium, a common misconception reported in the literature. When comparing the data from the pretest and the posttest, it becomes clear that 27% of students in the experimental group and 33% of students in the control group both shared the same common misconception regarding item 3. Only one student (7%) in the experimental group had this misconception, whereas there was no difference in the percentage of participants who held it in the control group.

For item 5, 75% of students in the control group and 20% of students in the experimental group still believed that the concentrations of NO and NOCl were equal, which is a common misconception reported in the literature. When comparing the pre-test and post-test results for the participants' common misconception for item 5, it is clear that 50% of students in the control group and 40% of students in the experimental group both shared the

misconception. While fewer students in the experimental group had the common misunderstanding for item 5 than in the control group, more students in the control group had the same misunderstanding.

For item 8, 42% of students in the control group and 40% of students in the experimental group agreed with the widespread misconception that the equilibrium constant K will be higher when equilibrium is restored after a decrease in the system's volume. This misconception was, however, shared by 33% of students in the experimental group and 40% of students in the control group.

The least performance gain was seen among participants in the experimental group on item 6, making it a special case. The misconception that, at equilibrium, K is less than 1 because the total moles of products are lower was held by 42% of students in the control group and 47% of students in the experimental group. The meaning of item 4 is also conveyed by item 6, but at a foundational level. The rate of the forward and reverse reactions will be equal if a system has reached chemical equilibrium, in other words. It was quite surprising to see how many more students who had correctly answered question 4 after the simulation intervention could not have answered question 6 correctly.

For item 11, 83% of students in the control group and 13% of students in the experimental group had the misconception that when a system's volume is decreased at equilibrium, when equilibrium is re-established, the concentration of NOCl_2 will be lower and the concentration of NOCl will be higher than the initial equilibrium. According to Hackling and Garnett (1984), students who shared this misconception were not fully aware of the connection between the consumption of reactants and the production of products during chemical reactions. The argument put forth by Cheung (2004) in support of the notion that incorrect LCP application can produce incorrect results. According to Berquist (1989), students frequently chose multiple-choice answers on a test about chemical equilibrium without having a comparable level of understanding for the underlying concepts.

For item 1, which stated that the rate of the forward reaction decreases as the reaction gets going, 93% of participants in the experimental group and 17% of participants in the control group provided the correct response. On the pre-test, only 25% of participants in the control group and 33% of participants in the experimental group had the right answer for item 1. The percentage comparison between the pre- and post-test shows a significant increase in the number of students who had the right answers.

For item 3, 93% of participants in the experimental group and 50% in the control group held the correct response. The proportion of participants with correct responses has increased significantly in the experimental group of students. For item 5, 50% of participants in the control and 93% of participants in the experimental group held the correct response respectively.

For item 10, 87% of the experimental and 0% of the control group's participants gave the right answer. While there is no change in the control group, there is a significant change in the proportion of students who have the correct response in the experimental group.

For item 11, 60% of the experimental group's participants and 0% of the control group's participants gave the right answer. While there is no change in the control group, there is a significant change in the proportion of students who have the correct response in the experimental group.

ANCOVA analysis

Research Question

After adjusting for pretest results, is there a statistically significant difference in the posttest means between the experimental group and the control group?

Research hypothesis

After adjusting for the pretest results, there will be a mean difference in posttest scores between the control and experimental groups.

ANCOVA

By accounting for variations in a covariate, a one-way analysis of covariance (ANCOVA) determines whether population means on the dependent variable are the same across levels of a factor, the independent variable (i.e., whether the adjusted group means differ significantly from one another). The covariate and the dependent variable distinguish individuals on quantitative dimensions, while the independent variable divides people into two or more groups (Green & Salkind, 2003). An ANCOVA is used to compare the posttest scores of the two groups (control and experimental), after subject heterogeneity—or naturally occurring individual differences—have been taken into account.

ANCOVA results

Results from a one-factor ANCOVA showed posttest scores were significantly higher for the experimental group ($M_{\text{postadj.}} = 7.27$, $SD_{\text{post}} = 1.387$) relative to the control group ($M_{\text{postadj.}} = 2.67$, $SD_{\text{post}} = 1.371$) after adjusting for pretest scores: $F(1,24) = 71.82$, $MSE = 1.497$, $p = 0.03$, $\eta_p^2 = 0.75$, $d = 3.33$. Cohen's d was converted to an attenuated effect size d^* using the procedure outlined in Thompson (2006). The adjusted group mean difference estimate without measure error correction for the post and pre-test scores was 4.2 with a Cohen's d of 3.04.

Using an alternate method reported by Cho and Preacher (2015)^[9], the effect size was determined. The adjusted group mean difference estimate without measure error correction for the post- and pre-test scores was 4.99 with Cohen's $d = 3.61$. Finally, the adjusted (for pretest scores) group mean difference estimate with measurement error correction for both pretest and posttest scores was 4.23 with Cohen's $d = 3.07$. The effect sizes indicate a strong relationship between the intervention provided and students' conceptual understanding of chemical equilibrium concepts. That is, participants who received the intervention had exceptionally high scores on the CEMT.

Conclusions

Figure 5 displays the percentage of correct conceptions held by participants in the experimental and control groups both before and after the study. The students in the experimental group gave a higher percentage of correct answers to the following questions (pre- and post-test percentages are shown inside the bracket). Item 1 (33%, 93%), Item 3 (60%, 93%), Item 4 (53%, 100%), Item 5 (20%, 67%), Item 7 (7%, 47%), Item 10 (20%, 87%), and Item 11 (27%, 60%) all received the highest scores. With items 6, 8, and 9, participants saw only slight improvements. Participants who received the experimental intervention demonstrated a remarkable improvement in their conceptual understanding

of chemical equilibrium concepts.

The study's findings were encouraging and supported the goal of investigating how well a simulation could support students' conceptual understanding of chemical equilibrium. The intervention appears to have had a significant impact on

students' conceptual understanding of the chemical equilibrium concepts discussed in the study, according to statistical significance from the independent samples t-test. The quantitative CEMT instrument has a reliability of $\alpha = 0.71$, which supports the validity of the tool.

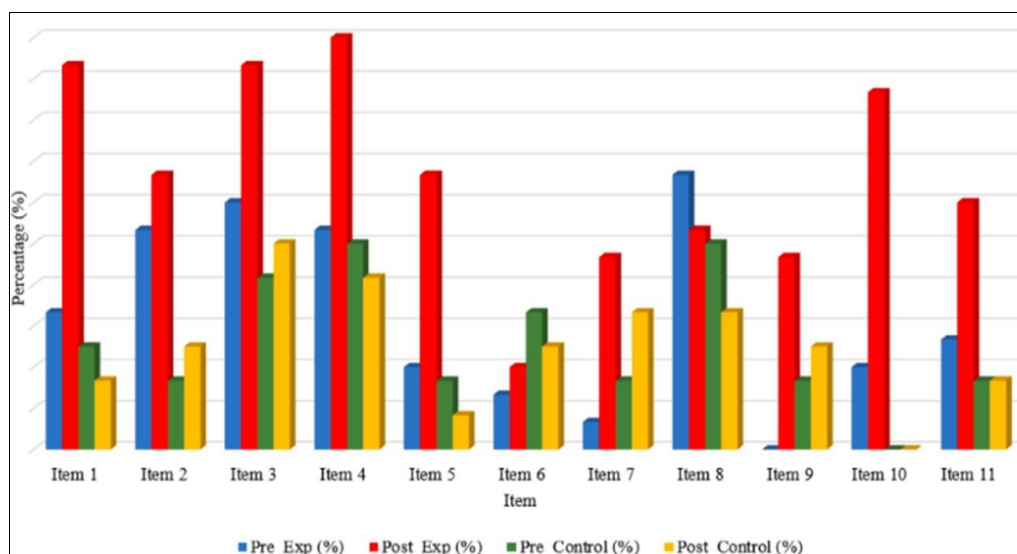


Fig 5: Graphical depiction of the pre- and post-phase participants in the control and experimental groups' percentages of correct conception.

Significance

- The primary significance of this study is based on a system's approach to chemical equilibrium using visual technology. No study examined chemical equilibrium from the viewpoint of a system, even though the numerous research studies mentioned above have revealed widespread misconceptions about chemical equilibrium among students,
- The simulations in this study simulate a chemical reaction at the particle level and include graphs that let students connect the data to the development of the reaction. The simulations also give students the chance to interact with technology,
- Both audio and visual components are present in the simulations that have been created. As a result, the simulations can accommodate students who prefer to learn visually, verbally, or both.

Limitations

The study did not address other common misconceptions about chemical equilibrium, such as the impact of temperature, catalysts, or the addition of inert gas. While simulations were developed to address these misconceptions, they were not included in the study due to time restrictions. These were the concepts that the simulations were intended to explore, but again, due to time restrictions, they did not.

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References

- Al Balushi SM, Ambusaidi AK, Al Suhaili AH, Taylor N. Omani twelfth grade students' most common misconceptions in chemistry. *Science Education International*,2012;23(3):221-240.
- Banerjee AC. Misconceptions of students and teachers in chemical equilibrium. *International Journal of Science Education*,1991;13(4):487-494.
- Bell RL, Trundle KC. The use of a computer simulation to promote scientific conceptions of moon phases. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*,2008;45(3):346-372.
- Bergquist W, Heikkinen H. Student ideas regarding chemical equilibrium: What written test answers do not reveal. *Journal of chemical Education*,1990;67(12):1000.
- Bilgin İ. The effect of cooperative learning approach based on conceptual change conditions on students understanding of chemical equilibrium, 2002.
- Brown DE, Hammer D. Conceptual change in physics. In *International handbook of research on conceptual change*. Routledge, 2009, 155-182.
- Bunce DM, Gabel DL, Samuel JV. Enhancing chemistry problem-solving achievement using problem categorization. *Journal of Research in Science Teaching*,1991;28(6):505-521.
- Cheung D. The adverse effects of Le Chatelier's principle on teacher understanding of chemical equilibrium. *Journal of Chemical Education*,2009;86(4):514.
- Cho SJ, Preacher KJ, Bottge BA. Detecting intervention effects in a cluster-randomized design using multilevel structural equation modeling for binary responses. *Applied Psychological Measurement*,2015;39(8):627-642.
- Demircioğlu G, Demircioğlu H, Yadigaroglu M. An investigation of chemistry student teachers' understanding of chemical equilibrium. *International Journal on New Trends in Education & Their Implications (IJONTE)*,2013;4(2):192-199.
- Ganasen S, Shamuganathan S. The Effectiveness of physics education technology (PhET) interactive simulations in enhancing matriculation students'

- understanding of chemical equilibrium and remediating their misconceptions. In *Overcoming Students' Misconceptions in Science*. Springer Singapore, 2017, 157-178.
12. Gorsky P, Finegold M. Using Computer Simulation to Restructure Students' Conceptions of Force. *Journal of Computers in Mathematics and science teaching*,1992;11(2):163-78.
 13. Gupta A, Fisher D. Technology-supported learning environments in science classrooms in India. *Learning Environments Research*,2012;15(2):195-216.
 14. Hackling MW, Garnett PJ. Misconceptions of chemical equilibrium. *The European Journal of Science Education*,1985;7(2):205-214.
 15. Hameed H, Hackling MW, Garnett PJ. Facilitating conceptual change in chemical equilibrium using a CAI strategy. *International Journal of Science Education*,1993;15(2):221-230.
 16. Heeg J, Bittorf RM, Schanze S. Learners' conceptions about the chemical equilibrium – A systematic Review. *CHEMKON*,2020;27(8):373-383.
 17. Huddle PA, Pillay AE. An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*,1996;33(1):65-77.
 18. Indriani A, Suryadharma IB, Yahmin Y. Identifikasi kesulitan peserta didik dalam memahami kesetimbangan kimia. *J-PEK (Jurnal Pembelajaran Kimia)*,2017;2(1):9-13.
 19. Johnstone AH. The development of chemistry teaching: A changing response to changing demand. *Journal of chemical education*,1993;70(9):701.
 20. Jones T, Berger C. Students' Use of Multimedia Science Instruction: Designing for the MTV Generation?. *Journal of Educational Multimedia and Hypermedia*,1995;4(4):305-20.
 21. Jusniar J, Effendy E, Budiasih E, Sutrisno S. Developing a three-tier diagnostic instrument on chemical equilibrium (TT-DICE). *Educación Química*,2020;31(3):84.
 22. Kousathana M, Tsapalis G. Students' errors in solving numerical chemical-equilibrium problems. *Chemistry Education Research and Practice*,2002;3(1):5-17.
 23. Moore EB, Chamberlain JM, Parson R, Perkins KK. PhET interactive simulations: Transformative tools for teaching chemistry. *Journal of Chemical Education*,2014;91(8):1191-1197.
 24. Nakhleh MB. Why some students don't learn chemistry: Chemical misconceptions. *Journal of chemical education*,1992;69(3):191.
 25. Nurrenbern SC, Pickering M. Concept learning versus problem solving: Is there a difference?. *Journal of chemical education*,1987;64(6):508.
 26. Omilani N, Elebute FD. Analysis of misconceptions in chemical equilibrium among senior secondary school students in Ilesa Metropolis in Osun State, Niger. *African Journal of Educational Studies in Mathematics and Sciences*,2020;16(2):1-13.
 27. Özmen H. Determination of students' alternative conceptions about chemical equilibrium: a review of research and the case of Turkey. *Chemistry Education Research and Practice*,2008;9(3):225-233.
 28. Phelps AJ. Teaching to enhance problem solving: it's more than the numbers. *Journal of Chemical Education*,1996;73(4):301.
 29. Polit DF, Beck CT. The content validity index: are you sure you know what's being reported? Critique and recommendations. *Research in nursing & health*,2006;29(5):489-497.
 30. Schank P, Kozma R. Learning chemistry through the use of a representation-based knowledge building environment. *Journal of Computers in Mathematics and Science Teaching*,2002;21(3):253-279.
 31. Schnotz W. An integrated model of text and picture comprehension. *The Cambridge handbook of multimedia learning*,2005;49(69):10-1017.
 32. Siswaningsih W, Nahadi, Widasmara R. Development of three tier multiple choice diagnostic test to assess students' misconception of chemical equilibrium. *Journal of Physics: Conference Series*,2019;1280(3):032019.
 33. Tao PK, Gunstone RF. The process of conceptual change in force and motion during computer-supported physics instruction. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*,1999;36(7):859-882.
 34. Üce M, Ceyhan İ. Misconception in chemistry education and practices to eliminate them: Literature analysis. *Journal of Education and Training Studies*,2019;7(3):202-208.
 35. Van Merriënboer JJ, Kester L, Paas F. Teaching complex rather than simple tasks: Balancing intrinsic and germane load to enhance transfer of learning. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*,2006;20(3):343-352.
 36. Voska KW, Heikkinen HW. Identification and analysis of student conceptions used to solve chemical equilibrium problems. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*,2000;37(2):160-176.
 37. Watson SW, Dubrovskiy AV, Peters ML. Increasing chemistry students' knowledge, confidence, and conceptual understanding of pH using a collaborative computer pH simulation. *Chemistry Education Research and Practice*,2020;21(2):528-535.
 38. Wheeler AE, Kass H. Student Misconceptions in Chemical Equilibrium. *Science education*,1978;62(2):223-32.
 39. Wu HK, Shah P. Exploring visuospatial thinking in chemistry learning. *Science education*,2004;88(3):465-492.
 40. Yan YK, Subramaniam R. Using a multi-tier diagnostic test to explore the nature of students' alternative conceptions on reaction kinetics. *Chemistry Education Research and Practice*,2018;19(1):213-226.
 41. Yezierski EJ, Birk JP. Misconceptions about the particulate nature of matter. Using animations to close the gender gap. *Journal of Chemical education*,2006;83(6):954.
 42. Zamanzadeh V, Rassouli M, Abbaszadeh A, Majd HA, Nikanfar A, Ghahramanian A. Details of content validity and objectifying it in instrument development. *Nursing Practice Today*,2014;1(3):163-171.