Santiago Sandi-Urena[1] / Giovanni Loría Cambronero[1] / Dayanna Jinesta Chaves[1]

Conceptualisation of Lewis structures by chemistry majors

[1] University of Costa Rica, School of Chemistry, Ciudad Universitaria Rodrigo Facio San Pedro de Montes de Oca, San Jose 2060, Costa Rica, E-mail: guillermo.sandiurena@ucr.ac.cr. https://orcid.org/0000-0003-3343-174X.

Abstract:
Lewis structures are the simplest model for students to communicate chemical information using chemical symbolic language. Thus, competence in Lewis structures is essential to progress in the study of chemistry. Proposals on how to teach/learn Lewis structures with inert rules abound, nonetheless, scant related educational research has been conducted. The present study is part of a larger investigation into the conceptualisation and use of Lewis structures by novices and experts. This study analysed data from a cross-sectional, 122-participant sample of chemistry majors at a large university in Costa Rica. Participants were prompted to draw Lewis structures, which rendered information on their representational competence. Analysis of mistakes in their representations shed light on participants' conceptualisation of Lewis structures. Responses to open-ended items further contributed in elucidating their conceptualisation. Findings suggest: (a) participants' competence to draw Lewis structures is deficient throughout the major; (b) participants relied significantly on memory and familiarity and not on understanding to draw Lewis structures; (c) most participants' limited understanding of Lewis structures stems from their using mental images and propositional representations for Lewis structures instead of mental models. Use of appropriate mental models could enable individuals to explain and predict chemical behaviour based on Lewis structures.

Keywords: chemical education research, college chemistry, Lewis structures, mental models, representational competence

DOI: 10.1515/cti-2018-0019

Introduction

Chemistry is extraordinarily visual not only in the observation of phenomena – macroscopic level – but also in its use of a complex symbolic language (Weininger, 1998). While the former may serve the purpose of fascinating individuals and capturing their attention and interest in the discipline, at least temporarily, the latter, when not mastered, may become a prolonged challenge for its learning (Marais & Jordaan, 2000). Learning chemistry requires making sense of events that are not directly perceptible. This quality renders chemistry inherently representational or symbolic (Kozma & Russell, 1997). Thus, the evolution of the discipline's highly complex symbolic *lingua-chimica* (Taber, 2009) is only natural (Weininger, 1998). To an expert in this specialised language, its complexities may be synonymous of intellectual sophistication and elegance. A beginning learner, on the other hand, besides struggling with the abstraction inherent to chemistry is challenged also by the equally abstract nature of representations that make up the new language, which is indispensable to comprehend the subject (Wu, Krajcik, & Soloway, 2001). The question arises whether the language of chemistry is effectively learned spontaneously through learning of the discipline or whether symbolism should be taught explicitly (Marais & Jordaan, 2000).

It has been accepted for decades now that students entering college present significant deficiencies in their conceptual understanding of chemistry and their ability to express themselves symbolically (Kozma & Russell, 1997). Recent evidence confirms the difficulties experienced by students to simply construct representations, let alone use them effectively (Grove, Cooper, & Rush, 2012). To complicate the matter, current evidence suggests advanced undergraduates and graduate students alike are not necessarily representationally competent (Cooper, Grove, Underwood, & Klymkowsky, 2010; Strickland, Kraft, & Bhattacharyya, 2010). Less than satisfactory learning is product of ineffective learning experiences, thus we have become interested in investigating the challenges instructors encounter when they use symbolic language to teach chemistry.

Lewis structures (Lewis, 1916) are the simplest model to get students started in the use of atoms and bonds – the basic semantic units of the chemical symbolic language – to efficiently communicate chemical information. Competence in their use is essential to progress in the study of chemistry, much like competence in the

Santiago Sandi-Urena is the corresponding author.

language of instruction should be. Thus, we utilise Lewis structure as a starting point in studying representational competence in chemistry. Although proposals to teach/learn inert rules abound (Ahmad & Omar, 1992; Contreras, Silvia, & Valenzuela, 1999), very scant educational research has been conducted in relation to Lewis structures (Cooper et al., 2010, 2013). As a whole, this abundance of, in principle, infallible instructions leads to the belief approaches to teaching Lewis structures – and other aspects of symbolism – are often similar to the way foreign languages should not be taught. It is quite clear memorising grammar rules void of meaning and application hardly enables learners to develop any decent degree of language proficiency. Learning sets of rules to draw Lewis structures, even if truly infallible, contradicts the purpose of developing representational competence as a scientific tool.

Mental representations

This section introduces basic propositions of cognitive science without intending to engage in an exhaustive discussion. According to Thagard (2005) the central hypothesis of cognitive sciences is that "*thinking can be best understood in terms of representational structures in the mind and computational procedures that operate on those structures.*" (p. 10) Even if not universally accepted, viewing the mind as an information processor comparable to a computer has contributed significantly in its understanding. Knowledge exists in the mind as these mental entities called representations, which are varied in nature to account for the multiple kinds of knowledge possible (e.g. rules, concepts, images). Friedenberg and Silverman (2011) argue for three characteristics of mental representations: (a) they must stand for an object in the external world (the referent), that is, they must have content; at its core, it is this property what renders them symbolic; (b) they must be grounded (related to their referent); (c) they must be semantic (have meaning).

In computers, algorithms operate on data structures to produce running programs. Analogously, mental procedures (*algorithms*) operate on mental representations (*data structures*) to produce thought and action (*running programs*) (Thagard, 2005). A proposition of outmost relevance in learning – in this case the symbolic language of chemistry – is that different types of mental representations support and nurture different types of mental procedures. Thus, the way information is encoded as mental representations are created, shapes what knowledge is available and what can be done with that knowledge, that is, what types of mental procedures are operative. Consequently, outcomes – behaviour or thought and action – are influenced by the nature of the mental representation. Evidence from work on physics problem solving has shown participants classified in different groups based on their type of mental representations utilised different strategies. Moreover, the qualities of their solutions differed substantially (Greca & Moreira, 1997; Ibrahim & Rebello, 2012). In a recent study in chemistry education, graduate student participants were "*unable to 'see' beyond the representations*" (Strickland et al., 2010). In the authors' words, the representations failed to represent. That is, the kind of processing expected was not observed, tentatively because the encoding of the information had not furnished the type of representation that would be consistent with those expectations. This disconnect was reported in reference to mechanistic reasoning in organic chemistry where students simply used external representations as pieces in a puzzle rather than reasoning tools to support solving chemical problems (Bhattacharyya & Bodner, 2005). In light of Friedenberg and Silverman's characterisation, in these two studies, representations were not grounded in a referent (at least not one that made them useful) and lacked semantic value (at least for their intended purpose).

Cognitive psychologists have put forth multiple forms of mental representations and ways to classify them (Friedenberg & Silverman, 2011). In this work we ascribed to the three major categories described by Johnson-Laird: (a) propositions, (b) mental images, and (c) mental models (Greca & Moreira, 1997; Johnson-Laird, 1998). Propositions are syntactic, abstract sentence-like structures that capture relationships between concepts. They include rules, series of symbols, such as equations, formulas, numbers, and definitions, and are meaningful only when applied to a proper context. Mental images "*represent how something looks from a particular point of view*" (Greca & Moreira, 1997; Johnson-Laird, 1998); they form through perception or imagination and represent the perceptible features of the corresponding real-world objects (Greca & Moreira, 1997). Mental models are constructed from visual perception or verbal comprehension. Their structure corresponds to the structure of the referent, that is, they are structural analogues of what they represent, though they do not need to be visualisable. Only indirectly, can we gather evidence for their existence and format. Mental models are personal constructs of use only to the individual and modifiable or dispensable upon revision. Working mental models support scientific sense making of the surrounding world in that they allow the individual to reason, explain and predict in relation to observed phenomena (Greca & Moreira, 1997; McClary & Talanquer, 2011). Thus the ability to create these working mental models determines scientific understanding and learning.

Research question

The leading question that guides this undergraduate exploratory research is: how do chemistry majors of different levels of expertise conceptualise Lewis structures? This work is part of a larger study that intends to characterise Lewis structure conceptualisation and use by novices and experts. The presumption is better understanding of the nature of representations constructed by learners may inform instructional design to more effectively support competence in Lewis structures. Ultimately, this knowledge may inform understanding of representation in chemistry, in general, and support representational competence development.

Methodology

Context and participants

A chemistry professor with experience in Chemical Education Research and two undergraduates double-majoring in chemistry and science education formed the research team. The study took place at an urban, public research university in Costa Rica with enrolments of just over 40,000 for undergraduates and approximately 5500 for graduates. Participants who volunteered were all chemistry majors in courses that correspond to first, second, and fourth year of the BS program. It is common at the research site for students from different years to overlap in their courses; for instance, to have individuals who have been in college for four years enrolled in second-year courses. Several reasons explicate such occurrence and should not be attributed to lack of academic competence. Readers interested in a detailed description of the program and the institution are referred to (Sandi-Urena, Romero, & Leitón-Chacón, 2018). We chose courses whose requirements prevented overlapping. These courses and the corresponding number of participants were: second semester General Chemistry (GC2, 50), first and second semester Organic Chemistry (OC1, 19, and OC2, 36, respectively), and a co-op course taken the semester of graduation (COC, 17). These courses are taught in chemistry-majors only sections. The tertiary system in Costa Rica is such that professional schools (medicine, pharmacy, law, etc.) do not require an undergraduate degree for admission. Students enter these schools directly upon completing secondary education. Therefore, chemistry majors at the research site do not pursue a degree in chemistry as a prerequisite for professional school but see themselves as future practicing chemists. Data collection occurred during the last quarter of the semester and the rate of participation was 100 % of students attending the courses.

Data collection

Figure 1 summarises the main steps of the study design. All information gathered was anonymous and collected the first calendar semester of 2017. To address our leading research question, we needed an instrument that would (a) gather information on participants' competence to draw Lewis structures and (b) elicit their thoughts on what they are and the reasons to create them (use and function). The instrument and all interactions with participants were in the language of instruction: Costa Rican Spanish. All references to the instrument content and responses shown here are based on translations of the original text. An initial draft of the instrument was created based on literature reports (Cooper et al., 2010) and discussions with upper level course instructors not involved with the study. This early version was pilot-tested with 15 students in a General Chemistry course for majors (second calendar semester of 2016). Readability and time required to complete were two main aspects considered during piloting. Only minor adjustments were necessary. A four-member panel of experts (instructors of advanced organic and inorganic chemistry courses) further contributed in the validation of the instrument. Each expert critiqued the instrument individually utilizing a review sheet designed by the research team. Experts assessed instrument design (e.g. clarity, relevance of items to address research questions) and contents (e.g. appropriateness of items to discriminate participants based on competence in drawing Lewis structures). They also had the option of contributing comments and concerns. We also inquired experts' opinion as which course in the BS curriculum should cover the topics in the instrument. Their consensus was the material should be presented in General Chemistry and refined and mastered in posterior courses. Following observations from the panel of experts, we left out two items that addressed the characteristics and differences between ionic and covalent bonds and ionic and covalent compounds. It was deemed that, in spite of their general relevance, these items did not fit in appropriately with the rest of the instrument and made it unnecessarily long. Other minor suggestions regarding wording were implemented.

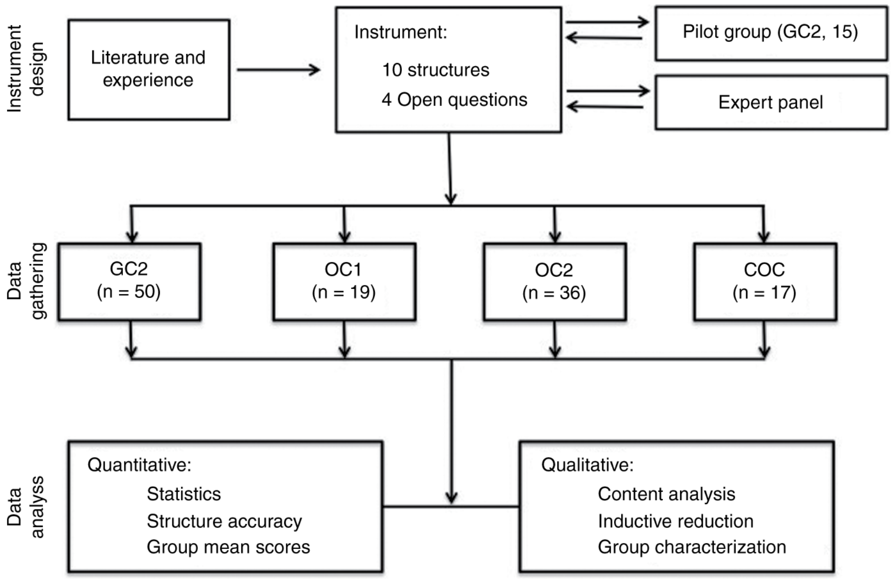

Figure 1: Main steps of the study design.

The final version of the instrument consisted of six items. Item 1 required participants to draw Lewis structures for H_2SO_4, SO_4^{2-}, $CuCl_2$, isocyanate ion (CNO^-), and sodium isocyanate. Item 2 asked to draw structures for NH_2^-, NO, CH_4S, C_2H_6O, C_3H_7NO. Species in Item 2 came from the literature (Cooper et al., 2010); our initial purpose in using them was to be able to compare data across institutions and countries. Responses were digitalised for storage. Responses to Items 1 and 2 were analysed for correctness and the types of errors made were registered for further analysis. Item 3 prompted participants to create a list of steps they used when drawing Lewis structures. It explicitly directed participants to list not the rules taught in class but the actual steps they had just taken to draw the structures in the previous items. Items 4 and 5 consisted of completing a sentence. Using this approach helps participants to focus, and be more specific and succinct in their responses. These sentences were "*A Lewis structure is…*" and "*A Lewis structure serves for…*" Item 6 was an open-ended question: "*What information can be obtained from a Lewis structure?*" Hand-written answers were digitalised. The research team conducted content analysis to extract emergent themes and trends.

Due to testing time constraints, for OC1, OC2, and COC we created two versions of the instrument, each containing either Item 1 or Item 2. For each of these courses, however, both versions were used, each administered to half of the participants so that we collected responses to all questions from all levels.

Data analysis

The wealth of information collected made it necessary to partition the analysis and report. We include here the analysis of Items 1 and 2 (drawing structures) and Item 4 ("*A Lewis structure is…*"). Final evaluation for Items 1 and 2 was dichotomous: correct/incorrect. In addition, errors were identified and tallied for each structure and by course. Item 4 probed participants' definition of Lewis structures, thus, we deem a standard definition necessary to guide content analysis. For this purpose, we turned to General Chemistry textbooks to extract the widely accepted components of a definition. The following statement is representative of our findings in several sources: "*A drawing that represents chemical bonds between atoms as shared or transferred electrons, the valence electrons of atoms are represented as dots.*" In general, textbooks describe Lewis structures as depicting the arrangement of atoms and distribution of valence electrons. A coding system was derived and refined from reviewing the responses and the accepted definition. The codes are: (1) *Connectivity*, presence of words describing the sequence or arrangement of atoms or referring to bonding but not mentioning electrons (e.g. "*Representation of the molecule, connectivity of bonds between atoms*"); (2) *Electrons*, strict reference to the representation of electrons with no mention to connectivity (e.g. "*A graphical representation of the distribution of electrons in a molecule*"); (3) *Complete*, explicit reference to both connectivity and electrons; (4) *Ambiguous*, attempted definition that lacks clarity (e.g. "*A representation of the shape and structure of a compound in a graphical manner*"); (5) *Circular*, expression that contributes no information beyond the re-statement of the term (e.g. "*A representation of the structure of a molecule*"); (6) finally, there were two *Unrelated* responses (e.g. "*Essential in chemistry*") which were dropped from the analysis (one each from OC1 and OC2). Similarly, the only three responses classified under *Ambiguous*, all in GC2, were eliminated from the analysis. One GC2 response that was left blank was also eliminated.

We used each individual response as unit of analysis. With the finalized codes, the three research team members coded the 122 responses independently and separately. After the first round, 4 % responses presented disagreement amongst the three coders. In 23 % of the responses, one coder was in disagreement with the other two. Code definitions were discussed once more and then researchers coded all 122 responses again independently and separately. After this second round, only 7 % had one coder disagreeing with the other two, and there were no responses for which all coders were in disagreement. These final disagreements were resolved through consensus. Code frequency distribution was calculated by course and trends were extracted.

Results and discussion

Table 1 shows the percentage correct distribution for structures in Items 1 and 2 by course. The correct average per course makes the assumption that all structures are equivalent in terms of assessment. Despite the inaccuracy of such an assumption, we include this value since this classical approach is customarily taken in course assessment. It is telling that no group reached what is considered a passing performance at the research site: achievement of 70 % or higher. This finding resonates with reports from other researchers who highlighted students at all levels, and some instructors, "*were more than a little confused about how to construct valid Lewis structures.*" (Cooper et al., 2010)

Table 1: Percentage correct by group for Lewis structures in Items 1 and 2.

Course (n)	Formula										Average
	H_2SO_4	SO_4^{2-}	$CuCl_2$	CNO^-	NaCNO	NH_2^-	NO	CH_4S	C_2H_6O	C_3H_7NO	
GC2 (50)	63	56	7	10	8	76	33	56	69	36	41
OC1 (19)	56	67	50	56	44	40	10	60	70	20	47
OC2 (36)	61	78	33	78	61	63	21	63	58	47	56
COC (17)	67	83	67	50	33	90	40	70	70	60	63

We borrowed the five right-most structures in Table 1 from Cooper et al. (2010). Although we do not see the drastic fall reported by these authors on going from one to two carbon-atom compounds, CH_4S and C_2H_6O, respectively, the decline for C_3H_7NO is rather sizable. Formulas were presented without structural cues which in the past has shown to constitute a barrier for students (Cooper et al., 2010).

Figure 2 shows student responses that are illustrative of the common mistakes we describe below. In all courses, the percentage correct for H_2SO_4 and SO_4^{2-} are dissimilar, differences ranging from 7 % to 17 %. We find this to be a first indicator that participants relied on familiarity and not so much on understanding when drawing Lewis structures. Otherwise, one would expect close to no difference in correct responses for these two structures. In all appearances, they used recollection of the structure as a static mental image. Although in principle a similar case, the difference in correctness between CNO^- and NaCNO is compounded with the inability to distinguish between ionic and covalent bonds in Lewis structures. In many cases, particular the first semester of Organic Chemistry and second semester of General Chemistry, the latter structure was shown with a covalent bond linking the counter ions. That participants failed to conceptualise the representation of ionic character was clear from their drawing of $CuCl_2$ as a covalent compound with localised bonds, too. Although participants failed to incorporate the non-directionality of the ionic bond, we conjecture they may *know* it but their drawings simply lack symbolic character. This is the case if drawings of structures are no more than *drawings* devoid of semantic nature. This also speaks to the preeminent role of familiarity. Students are typically asked to draw Lewis structures of molecules or ions (mono or polyatomic) and not so often of ionic compounds. If ionic compounds constitute a novel situation, one would hope transferring basic understanding of Lewis structures would produce a greater percentage of correct answers. The effect of familiarity emerged in Cooper et al. (2010), which they explained as memorised structural cues, as the correctness for their participants' Lewis structures dropped from 90 % for CH_3OH to 60 % for CH_4O. We put forth in such cases participants do not apply their understanding of Lewis structures – not even the rules to construct representations – but retrieve a mental image associated with a specific chemical formula.

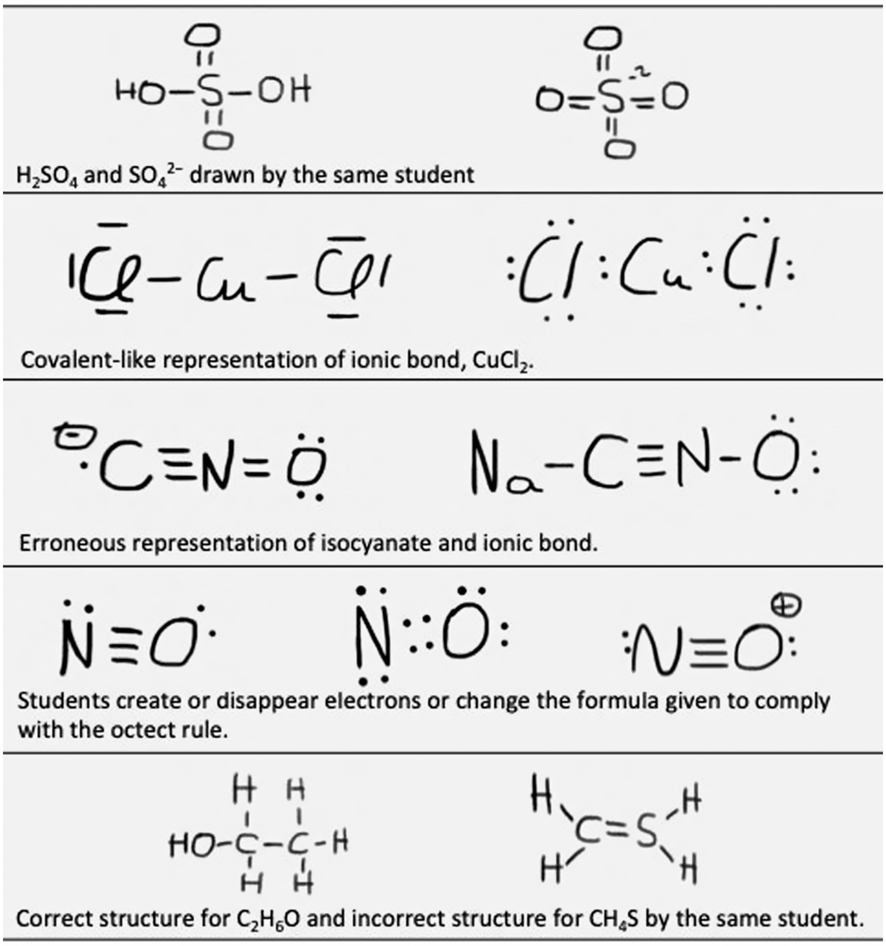

Figure 2: Student generated Lewis structures exemplifying common mistakes.

In and of itself, per cent correct for NH_2^- is worrisome but still between two and four times higher than correctness for NO. These results are not much different from what Cooper and collaborators reported in 2010. The main reason, as in their study, was a trend to assign complete octets to nitrogen and oxygen in NO in clear disregard of a shortage of electrons for that purpose. Fixation with the octet rule is most likely didaskalogenic in nature; it is instruction that underscores atoms "*want*" or "*need*" eight electrons to be "*stable*" (Cooper et al., 2010). The situation is even more troublesome from a representational perspective. Students seem unaware of the meaning of the symbols they use. Dots are electrons in name but do not represent the physical entity of an electron, they are not anchored to a referent in the external world. Apparently, there may be as many electrons as dots can be drawn with a pencil.

We wanted to elucidate whether the fixation with the octet rule and the lack of semantic nature in the use of the dots were two sides of a coin. We interviewed two seniors who clearly understood the symbolic nature of Lewis structures and did not impose the octet on NO. Yet, their first reaction when drawing the correct structure was claiming there was either something wrong with this molecule and suggesting probably what was meant was NO^-, or that NO would not exist because it did not abide by the octet rule. This continuing work suggests these two aspects may be separate and distinguishable. In our study, as well as in Cooper et al. (2010), application of rules and routines governed behaviour irrespective of the situation at hand. This kind of mindless behaviour is associated with learning environments that strive to create over-structured, fool-proof experiences (Ritchhart & Perkins, 2000), the type, we believe, the instructional proclivity for rules to draw Lewis structures and the octet rule promote.

We find further evidence for lack of semantic nature in students' drawings of ionic bonds as solid lines. In their set of rules, lines are bonds in name but, as with dots, they do not represent the physical entity of the external object. That is, they do not convey the properties of the referent but are limited to creating a 'picture' of it. A large proportion of participants seem unable to create working mental models to support scientific sense making and to allow them to reason, explain, and predict in relation to observed phenomena (Greca & Moreira, 1997). Instead, we hypothesise they create mental images with limited mental procedures associated (e.g. recalling, evoking). These mental images may suffice for immediate goals such as passing an exam but are not consistent with sound, meaningful learning.

Drawing a correct Lewis structure – especially one that is commonly used in introductory courses – does not imply thorough understanding of Lewis structures, their purpose and use. Likewise, the ability to verbalise a definition does not warrant understanding of the object or concept defined; nonetheless, the opposite, inability to do so suggests lack of basic comprehension. Table 2 shows the code distribution for the content analysis of participants' definitions of a Lewis structure.

Table 2: Code distribution by course for the item "A Lewis structure is...".

Course (n)	Complete (%)	Connectivity (%)	Electrons (%)	Circular (%)
GC2 (46)	12	23	6.2	52
OC1 (18)	10	21	16	47
OC2 (36)	8.1	22	30	38
COC (16)	29	35	18	18

Only a small percentage of participants returned a Lewis structure description that fully included the two components typically underscored by textbook authors and instructors: atom connectivity and valence electrons. Where definitions were incomplete and only one was mentioned, there was greater emphasis on connectivity than electrons, except for OC2. Neglect to consider electrons in the definition may underlie the license taken by participants to create them out of thin air to force completion of the octet when drawing a Lewis structure for NO. Electrons were added in the same way Grove et al. (2012) reported their participants used arrows in mechanisms: just to adorn and decorate their submissions as they thought it was expected of them but not in reflection of their representational meaning.

Circular definitions declined as participants were more advanced in their major; however, at 38 the percentage is still considerable for OC2. Given the study is cross-sectional, reasons for the drop may be compounded and include student desertion from the major. Nevertheless, these high percentages still evince failure to internalise the symbolic nature of Lewis structure representations. Take for example these responses: A Lewis structure is ..."*a way to see how a molecule is seen*" (OC2), "*a graphic representation of how a compound would look like*" (OC2), "*a way in which, it can be said, a molecule is seen*" (GC2). Such assertions underscore the suggestion participants' mental (internal) representations most likely take the form of mental images and not mental models. If this is the case, and given mental procedures enabled are dependent on the nature of the representations constructed, it may be unrealistic to expect students to use Lewis structures in the explanatory and predicting potential associated with mental models. Presumably, their use will be confined to identifying and matching formulas with their spatial atom arrangement – a stance driven most probably by instruction focused on test performance.

In response to such instruction, students develop a catalogue – that increases with and is polished by familiarity and exposure – from which they can retrieve images upon requests presented as chemical formulas. In their work with organic chemistry students, Shane and Bodner (2006) described the reduction of Lewis structures to verbal-linguistic representations that students used as "*collections of letters, lines, and dots that were not "symbols" because they didn't symbolise anything that reflected physical reality.*" (p.7) We discussed this above where we made reference to the inability of participants to representationally distinguish ionic and covalent bonds. Evidence from another study points at this same strategy when students' success in drawing even simple structures relies on explicit structural cues: a significantly greater number of students drew a correct structure for CH_3OH than for CH_4O (Cooper et al., 2010). In our interpretation, this observation follows from students creating separate and independent mental images linked to the individual chemical formulas. The label "CH_3OH" is associated with a certain "*collection of letters, lines, and dots*" but not so the label "CH_4O". Eventually, upon further exposure and practice, the two entries in their mental catalogue may overlap allowing a correct response to either prompt. Of course, there are also students who in actuality develop useful mental models.

In all appearances, for a considerable number of students drawing Lewis structures becomes the goal of drawing Lewis structures; that is, the representation displaces the referent and representations fail to represent (Strickland et al., 2010). In their study of chemistry graduate students' representational competence in organic chemistry, Strickland et al. (2010) illustrated participants' misuse of representations when they spoke of "*the arrows as the agents of change as opposed to the electrons.*" In a separate study, Bhattacharyya and Bodner (2005) referred to this kind of behaviour as "*essentially playing with puzzles.*"

It emerged from participants' responses that they viewed Lewis structures exclusively in reference to "molecules" and "compounds". All but one left out any sort of reference to unit formulas, ions, and atoms, despite the fact they had just represented them, along with molecules, while responding to the first items on the instrument. Although not within the scope of this report, this observation raises issues with chemical identity understanding and points back at the inability to representationally differentiate ionic and covalent compounds or bonds.

Conclusions

Representational competence is indispensable to achieve sound understanding of chemical phenomena and to communicate chemical ideas effectively (Kozma & Russell, 2005; Weininger, 1998). It is with Lewis structures that students typically start their forays into explaining chemical reactivity and communicating chemical information (Cooper et al., 2010). Therefore, we maintain that the characterisation of how students conceptualise Lewis structures is relevant to assist them in developing representational competence.

Findings from this work suggest participants' competence to draw correct Lewis structures was deficient across the chemistry curriculum, including graduating seniors. Students seem to rely on test taking strategies to meet their immediate course demands without necessarily developing thorough understanding. Other studies, conducted in significantly different contexts, have uncovered similar deficiencies even in quaternary education and beyond (Cooper et al., 2010; Strickland et al., 2010). Reliance on memory and familiarity by a significant fraction of the study participants support the contention they create snapshots of what molecules 'look like' to later access this specific static mental image upon prompting. Instead of working mental models, with their inherent explanatory and predictive power, instruction seems to stimulate encoding as mental images.

Likewise, for participants in this study propositional representations take prominence over working mental models, something that has been reported in Physics problem solving, too (Ibrahim & Rebello, 2012; Greca & Moreira, 1997). There is nothing inherently wrong with propositions; nonetheless, they are meaningful only when applied to a proper context and interpreted in reference to a mental model. The indiscriminate use of the octet rule in disregard of the context speaks to what Langer describes as mindless behaviour (Langer & Moldoveanu, 2000). Ritchhart and Perkins (2000) have identified instructional practices to cultivate mindfulness in the classroom, as well as practices that promote mindlessness. The greater project in which this study is nested intends to develop a pedagogical approach to mediate effective learning and understanding of Lewis structures based on research findings. Although still on the early stages of this project, we believe consideration of Mindfulness Theory (Langer & Moldoveanu, 2000) as a guiding tool to design instruction is worthwhile exploring.

Lastly, this report contributes uniquely to the international chemical education research community. Contexts in which similar research has been carried out are very limited in terms of type of institution, national origin, and language. The immediate step in this research line is to finish processing the entirety of the information gather with our instrument. Alongside, we aim at developing international collaborations to replicate this work in multiple research sites in countries clearly varied in terms of geography, language, and culture.

Supplementary Information

The instrument is available from the authors upon request.

Acknowledgments

The corresponding author thanks Dr. S. T. Arbucks who provided a suitable space and reliable internet to work on this project, as well as consumer grade 1,3,7-trimethylxanthine to finish this manuscript. Without their contributions this work would not have been possible.

References

Ahmad, W. Y., & Omar, S. (1992). Drawing Lewis structures: A step-by-step approach. *Journal of Chemical Education*, *69*(10), 791.

Bhattacharyya, G., & Bodner, G. M. (2005). "It gets me to the product": How students propose organic mechanisms. *Journal of Chemical Education*, *82*(9), 1402.

Grove, N. P., Cooper, M. M., & Rush, K. M. (2012). Decorating with arrows: Toward the development of representational competence in organic chemistry. *Journal of Chemical Education*, *89*(7), 844–849.

Contreras, M., Silvia, C., & Valenzuela, J. (1999). Estructuras de Lewis. Una visión aritmética. *Educación Química*, *10*(2), 119–122.

Cooper, M. M., Grove, N., Underwood, S. M., & Klymkowsky, M. W. (2010). Lost in Lewis structures: An investigation of student difficulties in developing representational competence. *Journal of Chemical Education*, *87*(8), 869–874.

Cooper, M. M., Corley, L. M., & Underwood, S. M. (2013). An investigation of college chemistry students' understanding of structure–property relationships. *Journal of Research in Science Teaching*, *50*(6), 699–721.

Friedenberg, J., & Silverman, G. (2011). *Cognitive science: An introduction to the study of mind*. Thousand Oaks, California, USA: Sage.

Greca, I. M., & Moreira, M. A. (1997). The kinds of mental representations – models, propositions and images – used by college physics students regarding the concept of field. *International Journal of Science Education*, *19*(6), 711–724.

Ibrahim, B., & Rebello, N. S. (2012). Using Johnson-Laird's cognitive framework of sense-making to characterize engineering students' mental representations in kinematics. In *AIP Conference Proceedings* (Vol. 1413, No. 1, pp. 219–222). College Park, Maryland, USA: American Institute of Physics.

Johnson-Laird, P. N. (1998). Imagery, visualization, and thinking. In Julian Hochberg, ed., *Perception and cognition at century's end* (pp. 441–467). San Diego, California, USA: Academic Press.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In John K. Gilbert, ed., *Visualization in science education* (pp. 121–145). Dordrecht: Springer.

Wu, H. K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *38*(7), 821–842.

Langer, E. J., & Moldoveanu, M. (2000). The construct of mindfulness. *Journal of Social Issues*, *56*(1), 1–9.

Lewis, G. N. (1916). The atom and the molecule. *Journal of the American Chemical Society*, *38*(4), 762–785.

Marais, P., & Jordaan, F. (2000). Are we taking symbolic language for granted? *Journal of Chemical Education*, *77*(10), 1355.

McClary, L., & Talanquer, V. (2011). College chemistry students' mental models of acids and acid strength. *Journal of Research in Science Teaching*, *48*(4), 396–413.

Ritchhart, R., & Perkins, D. N. (2000). Life in the mindful classroom: Nurturing the disposition of mindfulness. *Journal of Social Issues*, *56*(1), 27–47.

Sandi-Urena, S., Romero, R., & Leitón-Chacón, J. (2018). Chemical Education Research as an emergent field of work in Costa Rica. In *International and Multicultural Chemistry Education Perspectives* (pp. 9–25). Washington, DC: ACS Publications.

Shane, J. W., & Bodner, G. M. (2006). General chemistry students 'understanding of structure-function relationships. *The Chemical Educator*, *11*(2), 130–137.

Strickland, A. M., Kraft, A., & Bhattacharyya, G. (2010). What happens when representations fail to represent? Graduate students' mental models of organic chemistry diagrams. *Chemistry Education Research and Practice*, *11*(4), 293–301.

Taber, K. S. (2009). Learning at the symbolic level. In John K. Gilbert, ed., *Multiple representations in chemical education* (pp. 75–105). Dordrecht: Springer.

Thagard, P. (2005). *Mind: Introduction to cognitive science*. Cambridge, MA: MIT press.

Weininger, S. J. (1998). Visuality and the Semiotics of Chemistry. *Hyle*, *4*(1), 3–27.