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Development of the Bonding Representations Inventory To Identify Student Misconceptions about Covalent and Ionic Bonding Representations

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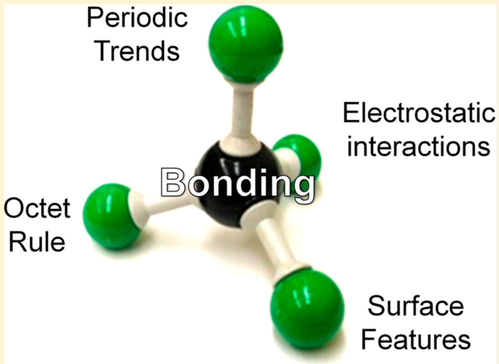
ABSTRACT: Teachers use multiple representations to communicate the concepts of bonding, including Lewis structures, formulas, space-filling models, and 3D manipulatives. As students learn to interpret these multiple representations, they may develop misconceptions that can create problems in further learning of chemistry. Interviews were conducted with 28 high school physical science, high school chemistry, and general chemistry students. The interviews focused on identifying student understanding of, and misconceptions about, covalent and ionic bonding representations through analysis of both student-created and expert-generated representations. Misconceptions about bonding representations were identified regarding four themes: (i) periodic trends, (ii) electrostatic interactions, (iii) the octet rule, and (iv) surface features. The Bonding Representations Inventory (BRI) was developed to quantify the prevalence of these misconceptions. The BRI was administered to 1072 high school chemistry, advanced placement chemistry, and general chemistry students across the United States. Content validity was determined through expert validation of the items, and concurrent validity was established by comparing the three groups of students. Reliability was determined through individual item analysis and through Ferguson's δ. Suggestions are offered for using the BRI in high school and general chemistry classrooms to inform the teaching of both bonding and representations.



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FEATURE: Chemical Education Research

■ INTRODUCTION

Bonding is commonly depicted in textbooks using a variety of representations.[1] However, the limitations of these representations are rarely discussed by the textbook writers.[2] Both Glynn[2] and Duit[3] discuss the importance of teachers helping their students identify not only the commonalities among representations, but also their limitations. A study conducted in Perth with 10 science teachers reported that only half of them ever discussed the limitations of models, and only two teachers reported discussing these limitations on a regular basis.[1] Meanwhile, students struggle to draw and interpret the physical properties inherent in Lewis structures.[4,5] Physical manipulative models may lead to confusion between ionic and covalent with learners believing "the stick" is an individual covalent bond.[6,7] Luxford and Bretz reported that student-created models of covalent and ionic bonding were useful for eliciting students' understandings and misconceptions beyond memorized definitions.[8]

A misconception is commonly defined as a mistaken idea, notion, or thought that is not grounded in scientific understanding. Misconceptions are not fleeting ideas, but rather are resistant to change.[9−11] Other terms used in the literature to describe these ideas include misunderstandings, naïve conceptions, and alternative conceptions.[12] These terms can be sorted into two categories: nomothetic terms and ideographic terms.[13] Nomothetic terms such as misconceptions, naïve conceptions, conflicting notions, classroom mismatches, and erroneous conceptions tend to be used in quantitative experimental studies and make comparisons to accepted scientific ideas. Ideographic terms such as alternative conceptions, children's science, developing conceptions, personal constructs, and intuitive beliefs tend to be used in studies that are more qualitative in nature and explore explanations constructed by students to make sense of their experiences. While each of these terms differs in subtle ways from the others, ultimately they are all used by researchers interested in knowing more about what students understand. The term "misconception" evokes comparisons to expert thinking. While the research described herein is interested in students' emerging ideas about bonding, the instrument used in this research—the Bonding Representations Inventory (BRI)—judges answers as correct or incorrect, and as such, the term "misconceptions" will be used in this manuscript.

Several misconceptions are reported in the literature regarding covalent and ionic bonding, describing students' mental models

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of covalent and of ionic bonding.[8,14−18] The predominant methodology in most of the bonding misconceptions research has been interviews and case studies with small numbers of students. While an interview can yield deep insights about a student's mental model of bonding, it is time-consuming to conduct and difficult to administer in classroom settings.

An alternative method to assess student understanding in a classroom setting is with paper-and-pencil multiple-choice concept inventories.[19,20] One way to develop a concept inventory (CI) is to conduct an extensive literature search on previously known misconceptions, capturing expert knowledge on those ideas, and then to develop questions to measure that knowledge.[21] An alternative approach to concept inventory design is to develop an interview protocol from prior literature that probes students' understanding, consistent with the National Research Council's call for students' conceptual understanding to be determined through educational assessments designed from interviews.[22] Analysis of the interviews then guides the design of the concept inventory questions and distractors. Tamir points out the richness of such distractors that are grounded in student responses.[23]

Chemical bonding misconceptions have been previously explored through the use of three concept inventories that focused on multiple aspects of bonding.[19,24−27] Peterson and Treagust developed a two-tier concept inventory exploring students' ideas about polarity, shape, intermolecular forces, and the octet rule.[19,25] (One-tier questions measure content knowledge,[28,29] while two-tier items ask students not only what the answer is, but also to indicate the reason why they believe their answer is correct.[27,30]) Tan and Treagust developed a second concept inventory by using questions from Peterson and Treagust's inventory, as well as from interview data about intermolecular and intramolecular bonds.[26] Othman and colleagues developed yet another concept inventory by combining questions from preexisting concept inventories and prior literature to explore students' ideas about bonding and the particulate nature of matter.[24]

While these three bonding concept inventories have contributed to a better understanding of students' knowledge about covalent bonding and ionic bonding, these inventories were developed from experts dictating knowledge to be known and looked broadly at the role of bonding in several different contexts. No inventories exist that focus exclusively on students' interpretation of external representations as a means of measuring their understanding of covalent and ionic bonding.

To explore student understanding of bonding and of bonding representations, a large study was designed to answer four research questions:

1. What do student-generated models of ionic and covalent bonding reveal about students' understanding of ionic and covalent bonding?
2. What information do students perceive to be encoded in multiple representations of ionic and covalent bonding?
3. What do high school chemistry and general chemistry students' explanations of multiple representations reveal about their understanding of ionic and covalent bonding?
4. How prevalent are students' misconceptions of covalent and ionic bonding as revealed through the use of representations?

Findings regarding Question 1 have been published.[8] Findings regarding Questions 2 and 3 will be reported in forthcoming manuscripts. The focus of this manuscript is to describe the development of the BRI, evidence for the validity and reliability of the data generated from it, and findings regarding Question 4 as measured by the BRI.

■ INVENTORY DEVELOPMENT

The goal in developing the Bonding Representations Inventory was to design a concept inventory that would be grounded in students' understandings of bonding representations and to create a quantitative measure of those understandings, with evidence for the validity and reliability of the data. The BRI was created to measure misconceptions about bonding and bonding representations as revealed through analysis of interviews with both general chemistry students (GC, $n = 13$) and high school students (HS, $n = 11$). These interviews were conducted post-instruction and postassessment by the classroom teacher on chemical bonding, Lewis structures, and valence shell electron pair repulsion (VSEPR). The interview protocol consisted of asking students to create models and discuss a series of expert-generated representations of CCl_4, PCl_5, and NaCl, with an emphasis on eliciting their ideas about bonding.

Through the analysis of the interviews, four themes emerged regarding student misconceptions when students were asked to determine the type of bond depicted in a representation: (i) periodic trends, (ii) electrostatic interactions between atoms, (iii) surface features associated with the representations, and (iv) the octet rule. Traditionally, bonding is initially taught using a dichotomy for classifying molecules and compounds as either covalent or ionic.[31] The concept of bonding types being better represented along a continuum is not often emphasized in high school or general chemistry curriculum, despite the progression of learning requiring a shift from consideration of metals and nonmetals to electronegativity and the differing degrees of polarity.[31,32] Research suggests that a dichotomous approach to teaching bonding can act as a learning impediment and interfere with further learning about bonding as a continuum.[16] None of the students interviewed mentioned, let alone discussed, this continuum—choosing instead to discuss bonding using only a dichotomous classification of covalent versus ionic.

Item Development

Student quotes were used to develop concept inventory questions grounded in students' understandings of the bonding representations used in the student interviews. To illustrate how the student quotes were used to develop the items, consider the following example. During the interview, students were asked, "What do the different parts of the representation mean?" regarding Figure 1. Below are three students' explanations of the role of the brackets in the representation. Figure 2 shows how these student quotes were subsequently used to develop a one-tier multiple-choice question.

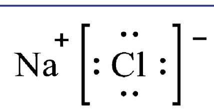


Figure 1. One representation of NaCl used in student interviews.

And these brackets might be something about concentration.

[Mekelle, GC]

The brackets show that that is the more electronegative element that stole the element... stole the electron.

[Nikki, GC]

In the representation, $Na^+[:\ddot{\underset{..}{Cl}}:]^-$ what information is communicated by the use of brackets?

A. The concentration of the ions.
B. The Cl^- ion has all of the electrons.
C. The Cl atom has gained an electron.
D. The Cl^- ion needs to lose one electron.

Figure 2. One-tier multiple-choice question as it appears on the final version of the BRI.

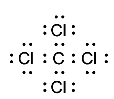
> *I think they [brackets] mean that the... that the negative are like the fact that it needs an electron to like be taken from the... I guess, from the chloride. I guess sort of separating it from the Na plus.*
>
> [Sierra, GC]

Both the question stem and question distractors were derived directly from the student interviews. The language of the distractors was kept as true to the meaning and phrasing of the quotes as possible. For example, the quote by Mekelle is represented nearly verbatim in distractor A. Nikki's idea that the more electronegative Cl atoms stole the electron is represented in the correct answer C, while Sierra's answer that the brackets show that the negative ion needs electrons taken from it is represented in distractor D. Distractor B, while not derived from discussion of Figure 1, did emerge from an interview as a student described Lewis structures. April (GC) stated

> *This [dots in Lewis structure of CCl_4] is all the electrons that are in the molecule.*

This wording was incorporated into the question to identify students who think that the dots represent *all* the electrons in a substance, rather than only the valence electrons. When creating two-tier items (see for example, Figure 3), it is important that each distractor in the first tier is written to allow for a plausible reason in the second tier.

5. Which is true for the bond between C and Cl?
   A. The C transfers one electron to the Cl.
   B. The Cl transfers one electron to the C.
   C. Equal sharing of electrons between C and Cl.
   D. Unequal sharing of electrons between C and Cl.



6. The reason for my answer to question #5 is:
   A. The dots are evenly spaced between C and Cl.
   B. C and Cl have similar, but not identical electronegativities.
   C. Each Cl needs 8 valence electrons, so it takes from the C.
   D. Cl already has electrons so C needs the electrons more than Cl.

Figure 3. An example of two-tier questions on the BRI. The first question measures student understanding, and the second question asks the student to indicate the reason for choosing the answer in tier one.[33]

Pilot Test

Analysis of the interviews and an exhaustive coding for themes lead to the creation of an alpha version of the Bonding Representations Inventory (BRI-α), which consisted of 32 questions (10 two-tier and 12 one-tier items).[33] The representations from the interview protocol were converted from color to grayscale for ease of use in classroom settings (i.e., to avoid the prohibitive costs of color printing and photocopying). The questions were reviewed by a panel of five experts who all were instructors of general chemistry to establish content and face validity. The BRI-α was administered to students enrolled in a second-semester general chemistry course at a large predominately undergraduate institution in the midwestern United States. Of 390 students enrolled in the class, 247 students completed the inventory and consented for their data to be used for research purposes. On the basis of responses from the experts' reviews, two student validation interviews, and item analysis of the pilot data, questions were removed or modified. For example, questions were eliminated that did not clearly focus upon one of the four misconceptions themes that emerged from the analysis of interviews. Questions were modified to ensure that each question included a representation of bonding, and for questions that were quite similar to one another, one of the "duplicates" was eliminated. The final version of the BRI consisted of 23 multiple-choice questions (7 one-tier and 8 two-tier questions) in a paper-and-pencil format, all of which included at least one bonding representation and all of which focused on one of the four themes identified through analysis of the student interviews conducted to better understand how students distinguish between ionic and covalent bonding.[33]

■ DATA COLLECTION

Fifteen teachers at 14 high schools located in seven different states across the United States agreed to participate in the full study of the BRI. Of the 15 high school chemistry teachers, five taught high school advanced placement (AP) chemistry courses and 12 taught first year high school (HS) chemistry courses. Eight of the 14 schools were public schools; the remaining six schools were private schools. There were three urban schools, nine suburban schools, and two rural schools. High school teachers were given a $25 gift card to Flinn Scientific for implementing the inventory.

At the undergraduate general chemistry level, the BRI was administered to students taught by 11 instructors located in six different states across the country. Of the 11 instructors, six instructors taught at public institutions, while five taught as private institutions. Students in these general chemistry courses came from four community colleges, four comprehensive programs, and three liberal arts programs.

Teachers who were participants in professional development programs focused on inquiry instruction and assessment were invited to participate. Each teacher requested a specific number of copies of the inventory. Inventories were mailed, and teachers were provided with a postage-paid label to return them after students responded. Teachers were directed to implement the BRI postinstruction and postassessment of bonding and Lewis structures. Teachers were asked to read a script to their students containing instructions for taking the BRI and to instruct all students to anonymously indicate on the answer sheet whether they were willing, or not, to allow their data to be used for research purposes. Instructors were asked to give students 15−20 min to respond to the questions on the BRI. As incentive to use the BRI in their classroom, a summary of student performance on the BRI was provided for the teachers, individually.

The BRI was administered to N = 1036 high school students, and 725 students completed the inventory. Of those 725 students, 433 HS chemistry students and 192 AP students granted consent for their answers to be scored for research purposes. The BRI was also administered to N = 1095 undergraduate general chemistry students, with N = 447 students completing and giving consent for their answers to be used for research purposes.

■ DATA ANALYSIS

The data were entered into an Excel spreadsheet as raw responses, that is, the students' answers of A, B, C, or D for each item. Students who selected invalid choices such as distractors that did not exist or created designs and patterns with their responses were removed from the study. The two-tier items were considered first as individual, one-tier items and then later as paired items by graphing students' paired responses of AA through DD. The raw data were then converted to binary data with the correct answer coded as 1 and any incorrect answer being as 0. The binary data were used to calculate total scores. Psychometrics such as item difficulty, item discrimination, and Ferguson's δ were calculated using Excel. Both the raw data and the binary data were uploaded into SPSS to calculate descriptive statistics and reliability coefficients.

Descriptive Statistics

Table 1 summarizes the descriptive statistics for both one-tier and two-tier scoring of the BRI across AP, GC, and HS students. Score distributions are shown in Figure 4. The results for each group were significantly different from a normal distribution for both one-tier and two-tier analysis. Therefore, nonparametric techniques were used for data analysis.

Table 1. Descriptive Statistics for BRI Using HS, GC, and AP Student Responses

Statistic: 1-Tier (2-Tier)	Advanced Placement Chemistry	General Chemistry	High School Chemistry
N of Students	192	447	433
N of Items	23 (15)	23 (15)	23 (15)
Mean ± St. Dev.	14.23 ± 4.57 (8.21 ± 3.23)	12.47 ± 3.94 (7.15 ± 2.76)	8.71 ± 3.20 (5.48 ± 3.15)
Ferguson's δ Values	0.97 (0.96)	0.97 (0.94)	0.94 (0.91)

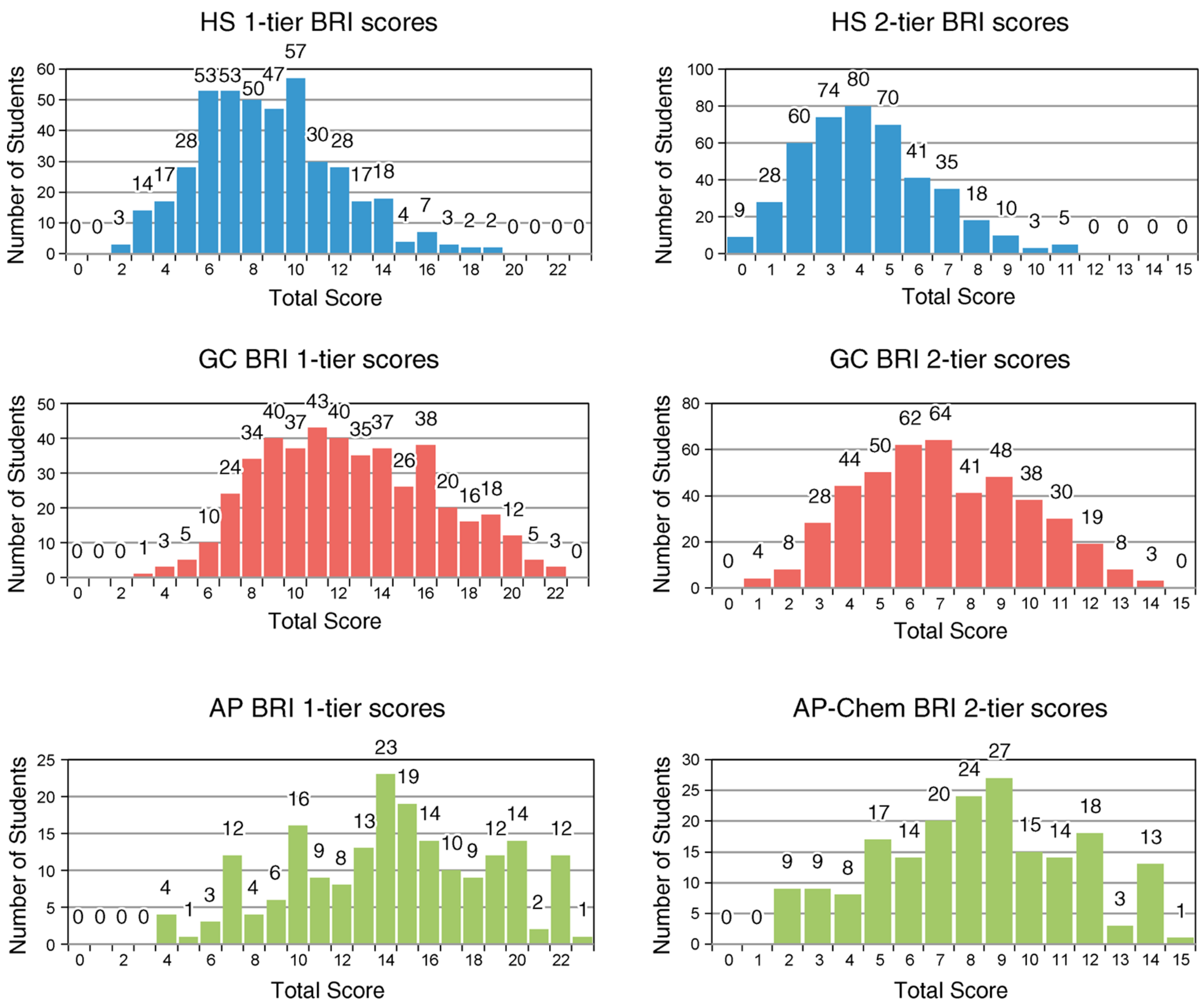


Figure 4. Distribution of scores on the BRI for HS, GC, and AP students.

Neither a floor effect (large numbers of students scoring zero) nor a ceiling effect (large numbers of students earning a perfect score) was observed. Test discrimination was measured by calculating Ferguson's δ values (Table 1). Values greater than 0.9 indicate scores are broadly distributed with good discrimination power among student samples.[34] Ferguson's δ for all three groups exceeded the ideal value of 0.9, meaning that more than 90% of all possible scores were represented in each of the samples.[28]

The majority of the 23 items on the BRI items performed within the acceptable range of difficulty and discrimination based on the one-tier data analysis. Item difficulty is reported as the percentage of students answering correctly; therefore, values below 0.3 are considered difficult questions, while difficulties above 0.8 suggest an easy item.[35] The average item difficulty for the HS student data set was 0.42 and ranged from 0.13 to 0.71, while the average item difficulty for the AP student data set was 0.62 and ranged from 0.34 to 0.94. The GC student data fell between the HS and AP student data with an average item difficulty of 0.54, with items ranging from 0.28 to 0.87. Overall, no items were uniformly difficult or uniformly easy across all three groups of students.

Item discrimination (D) indicates how well an item can discriminate between the 27% of the top-performing students and the 27% of the lower-performing students when comparing their individual answers with their total score.[28] The HS student data had D values ranging from 0.03 to 0.56 and an average of 0.51. The AP student data had D values ranging from −0.12 to 0.77 with an average value of 0.50. The GC student data had D values ranging from 0.07 to 0.64 with an average value of 0.41. There were no items with poor discrimination values across all three groups of students.

The plots of item discrimination and difficulty versus one another (Figure 5) provided additional insight into the performance of individual items and the BRI as a whole. Items 1 and 20 were easier items with low discrimination for the AP chem and GC students, meaning that students in both the top and bottom quartiles answered the item correctly. Items that were considered difficult would be also expected to have low item discriminations. Figure 5 shows that seven items fell within the difficult item−low discrimination category for the HS chem students, while only two items for the GC students, and no items for the AP chem students, were considered difficult with low discrimination. The overall distributions of the discrimination−difficulty points shift across the three courses suggesting that as students gain knowledge in chemistry, they were able to answer more items correctly. Hence, the corresponding shift in difficulty and higher discrimination indices is observed, suggesting that the students have less fragmented understanding.

Reliability

The internal consistency, as measured by Cronbach's α, indicates how closely the questions measured the same construct. Acceptable values are greater or equal to 0.7, according to Cronbach.[36] Values below 0.7 indicate weaker correlations between items. The α values for the AP students' data exceeded 0.7 for both one-tier (α_1 = 0.80) and two-tier analysis (α_2 = 0.72). Alpha values for the HS (α_1 = 0.54, α_2 = 0.45) and GC (α_1 = 0.70, α_2 = 0.60) data did not exceed 0.7, raising the question as to whether the data can be considered reliable or not. However, the historical practice of reporting α values for assessment instruments has recently come under scrutiny. The α value is an inappropriate indicator of reliability for concept inventories owing to the fragmented knowledge being measured.[28] As students construct knowledge, there are gaps, errors, and omissions in learning based on their prior experiences.[37] The BRI was developed to specifically target misconceptions and to explicitly probe for the gaps in students understanding that exist about covalent and ionic bonding. As such, when students' responses indicate they hold these misconceptions, the BRI would not likely measure a strongly connected knowledge structure that would be required to achieve an α value greater than 0.7.[28] The higher α values for the AP students suggest they hold a less fragmented framework of understanding for covalent and ionic bonding.

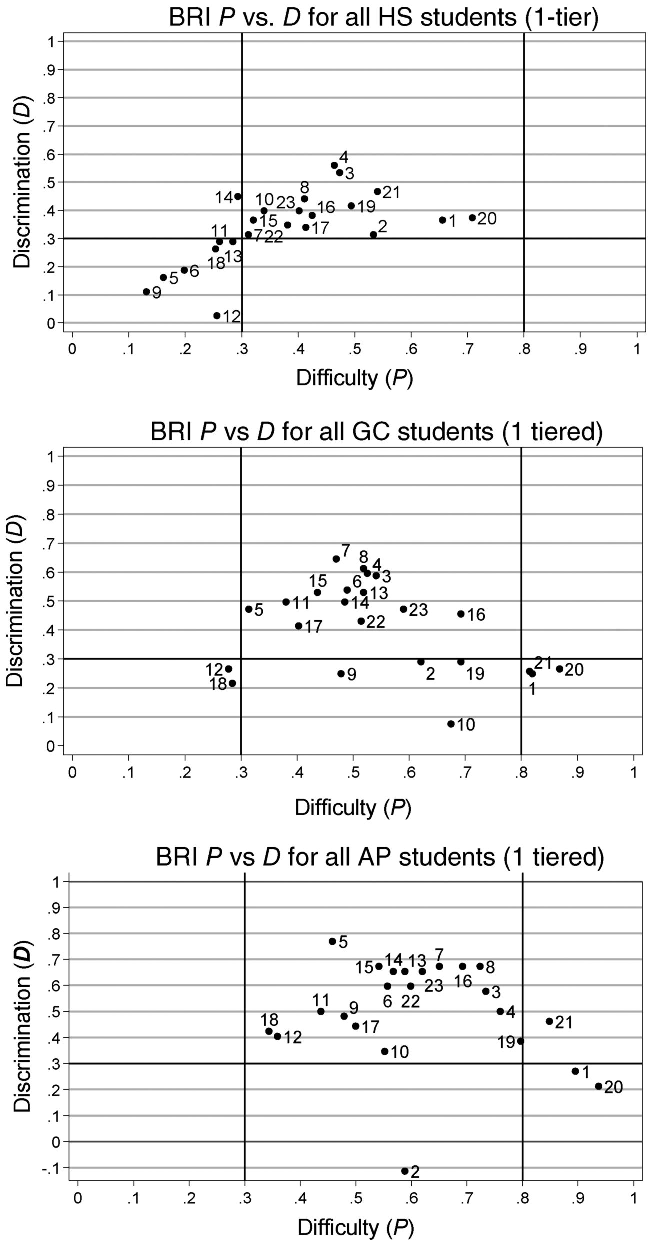


Figure 5. Difficulty versus discrimination plots for HS Chem, GC, and AP Chem students on BRI.[33]

Validity

Several forms of validity were examined to establish the validity of data generated by the BRI. Content and face validity were established when five general chemistry instructors, two of whom were also inorganic chemistry instructors, reviewed the

Table 2. Misconceptions Identified with the BRI for HS, AP, and GC Students

Misconceptions	Item Distractors
1. Periodic Trends	
Electronegativity	
Covalent bonds have very different electronegativities	1A and 2B[a,b,c]
Carbon is more electronegative than chlorine	13A
Metals and Nonmetals	
Inability to classify as metals/nonmetals	20A and 21A; 20A and 21B; 20A and 21C
2. Electrostatic Interactions	
Sharing electrons	
NaCl shares electrons	3A and 4C;[a,b,c] 11A
Slightly different electronegativities means equal sharing	5C and 6B;[b] 13C[a]
Transferring electrons	
Covalent CCl_4 has a transfer of electrons	5A and 6C; 16B
Covalent PCl_5 has a transfer of electrons	2D; 9B; 19A
Electrons transfer to neutralize charge	10D; 12C
Transfer of electrons is more accurate than attractions	11B[a,b,c]
Cations get rid of electrons to become stable	12D
A bond can be both sharing and transferring electrons	3C; 16C; 16D
Attractions	
Ions of the same type attract to one another	11C
Two electrons attract to one another to form bonds	19B
NaCl molecule units attract to form lattice structures	17A and 18B; 17B and 18B;[a,b,c] 22C and 23A; 22C and 23D
3. Octet Rule	
Bonds form to get eight electrons	5C and 6C;[a,b] 5D and 6C; 9A;[a]12B;[b,c] 22C and 23D
Only 1 Na and 1 Cl can bond	17A and 18A; 22A and 23D
4. Surface Features	
Spacing	
Spacing of dots between atoms indicates equal sharing	5C and 6A[a]
Similar spacing indicates same bond type	7A and 8B; 14A and 15A; 14B and 15A
Bonds = lines	17D and 18D; 22D
Dots represent all the electrons in the compound	10B[b]
Bond type cannot be determined without ± showing	7D and 8C; 14D and 15D
Bond type depends on atoms being labeled	7D and 8D;[a,b] 14D and 15C[b]
5. Term confusion	1B and 2C; 20B and 21D

[a]Distractor significant misconception as detected by 10% above random chance for HS students. [b]Distractor significant misconception as detected by 10% above random chance for GC students. [c]Distractor significant misconception as detected by 10% above random chance for AP students.

BRI-α version of the inventory. Because the BRI was administered to students in various stages of understanding about the construct of bonding, it would be expected that students enrolled in higher-level courses ought to perform better on the inventory. Concurrent validity is defined as a measure used to determine the degree to which a measure correlates with a criterion, namely, expected outcomes.[38] Students enrolled in an introductory chemistry class such as HS chem would be expected to perform more poorly than students in AP chem courses. It would also be expected that GC students would overall have a higher mean on the BRI than the HS chem as most of the GC students would have previously taken HS chem courses. Given that only higher ability students are typically enrolled in AP chemistry, it is not surprising that the mean for AP chem was higher than that of GC.

To determine whether the differences in AP, GC, and HS scores were significant, a one-way analysis of variance (ANOVA) would typically be used, as long as the data fit the underlying assumptions. However, the distributions of the three groups of students all violated the assumption of normality for both one-tier and two-tier scoring. Therefore, Kruskal–Wallis H tests were used to calculate and compare the relative rankings of the data.[39] Kruskal–Wallis tests revealed significant effects of class type on total BRI scores when scored as a one-tier instrument [$\chi^2(2) = 268$, $p < 0.001$] and when scored as a two-tier instrument [$\chi^2(2) = 294$, $p < 0.001$]. A p-value < 0.01 indicates that the ranks may be different, and suggests that the three groups should not be considered equivalent. Posthoc Mann–Whitney U tests were conducted in order to look for significant differences between the AP and GC students, the GC and HS students, and finally between the AP and HS students, using a Bonferroni adjusted α value of 0.003 to protect against Type 1 error (incorrect rejection of the null hypothesis). The Mann–Whitney U tests showed significant differences in one-tier scores between AP Chem and GC ($p < 0.001$, $r = 0.19$), between AP Chem and HS Chem ($p < 0.001$, $r = 0.53$), and between GC and HS Chem ($p < 0.001$, $r = 0.46$). The Mann–Whitney U tests also showed significant differences in two-tier scores between AP Chem and GC ($p < 0.001$, $r = 0.16$), between AP Chem and HS Chem ($p < 0.001$, $r = 0.54$), and between GC and HS Chem ($p < 0.001$, $r = 0.50$). This means that both the GC and the AP Chem students significantly outperformed the HS Chem students, and the AP students performed significantly better than the AP Chem students. As students gain additional instruction in bonding, they perform better on the BRI, thus providing evidence for concurrent validity of the data generated by the BRI.

PREVALENCE OF BONDING MISCONCEPTIONS

The BRI was designed to assess misconceptions across the four themes that emerged from analysis of the interviews across a variety of bonding representations. For example, Questions 5 and 6 contain several statements that measure across three themes (Figure 3). Question 5 asked students to consider the bond between C and Cl in terms of the transfer or sharing of electrons. They are then asked for their reasoning in Question 6 for which they can select between surface features, electronegativities, and the octet rule. If a student selected C for Question 5 and selected A for Question 6, based on the interview data it was determined that the students were focusing on the surface features; that is, spacing of the dots between atoms indicates equal sharing (Table 2). Another idea that students could hold for Questions 5 and 6 is that bonds form "in order to get eight electrons", which was indicated through a response of 5C and 6C. In this case, the students' response patterns showed that the students were less concerned with the phrase that the Cl takes from the C and seem to instead be focusing on the fact that each Cl needs to fit the octet rule. On the other hand, students also responded through pairing 5C and 6B, indicating that slightly different electronegativities means equal sharing of electrons, and pairing 5A and 6C which showed they considered covalent CCl_4 as having transferred electrons.

Some misconceptions were more prevalent than others, with a specific response being chosen by 10% of the students as the designated cutoff.[40−42] Caleon and Subramaniam suggested dividing misconceptions into *significant* misconceptions and *common* misconceptions.[43] Significant misconceptions included distractors that were chosen at a 10% greater than random chance (e.g., 35% on a four-choice item). In the case of the two-tier Questions 5 and 6, there are 16 combinations that the student could choose if answering randomly; therefore, random chance would be about 6%. For example, 23% of high school students selected both 5C and 6A, which means that the idea that the spacing of the dots between atoms indicates equal sharing is considered to be a significant misconception. Each prevalent misconception can be classified based on one of the themes that students used in qualitative interviews when discussing how to distinguish between covalent and ionic bonding (Table 2).

Some of the misconceptions measured by the BRI have been reported in prior literature. As in Taber's work,[14−16] HS chem, GC, and AP chem students clung to the notion of atoms needing eight valence electrons in order to explain bonding, with students selecting the corresponding distractors at 10% above random chance. The sharing of electrons was often used to describe ionic bonding, as shown by students HS chem, GC, and AP chem students who selected the two-tier choices that NaCl is covalent because Na and Cl share electrons. When explaining the ionic bonding in NaCl in terms of sharing electrons, students associate the term sharing with a social definition rather than an electronic definition to describe that the electron is attracted to both nuclei.[9,17] Much like the students in Taber's study, the students in all three course types struggled to move beyond understanding the formation of ions owing to electron transfer in order to recognize that the resulting ions are attracted to one another.[14−16] The finding that students believe NaCl forms discrete molecules that are then attracted to one another was also found in Peterson and Treagust's study using their concept inventory.[19] Other misconceptions measured by the inventory that focus on interpretation of bonding representation features are unique to the BRI. For example, there are no previous reports in the literature on bonding that students cannot classify bonds as covalent or ionic because of the representations not including the labeling of atoms.

CONCLUSIONS AND IMPLICATIONS

The descriptive statistics and psychometrics suggest that the items on the BRI are generating valid and reliable data regarding student misconceptions about multiple representations of covalent and ionic bonding. Students with more chemistry coursework perform better. The lower Cronbach α for HS students as compared to GC and AP students suggests that the HS students may hold a more fragmented understanding of chemistry. The distributions of scores for the HS, GC, and AP students suggest that the inventory as a whole is neither too hard nor too easy for any one group of students. The inventory is able to detect misconceptions held by all three groups of students.

The large sample size (N = 1072) and diversity of schools and institutions across several states from which data were collected suggests that the BRI is likely to be useful in most high school and general chemistry settings. Given that only 10−15 min is required for students to respond, and the representations are all in grayscale, the BRI is easy to administer for classroom use. The BRI could be used to determine the effectiveness of curricular or pedagogical interventions designed to address bonding misconceptions. The BRI could be used as formative assessment by teachers to assess what ideas students hold about bonding from previous courses, for example, to examine what ideas students hold from HS chemistry when beginning AP chemistry, what ideas GC students hold from high school, or even what ideas upper-level university students in inorganic chemistry retained from general chemistry. The Bonding Representations Inventory offers an easy tool for instructors to quickly and efficiently test their students' understandings of representations and bonding beyond rote memorization of rules such as "metal bonding with a nonmetal" versus "two nonmetals".[8]

Limitations

While this manuscript details evidence for the validity and reliability of data generated by the BRI, there are limitations to this study, as there are in all research investigations. Due to the anonymous collection of data, validation interviews with students on the item wording at the high school level was unavailable. Further validation may be needed in order to further determine the cause of the low Cronbach α value for the HS chem students. For example, there may be additional misconceptions not measured by the inventory, or additional validation interviews might determine whether the wording of the items confused HS students. In addition, this study did not focus on identifying different ways to *prevent* or to *change* students' misconceptions. The study also did not investigate the root causes of the misconceptions that were uncovered through the students' interviews and the resulting Bonding Representations Inventory. Additional research would be needed in order to determine causality of the covalent and ionic bonding misconceptions measured on the BRI. There is also a need for development of pedagogy and curricula that might be used to prevent or dispel these misconceptions.

Colleagues interested in obtaining a copy of the BRI for classroom use or additional research should contact the corresponding author.

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Notes

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