Students' Conceptions of Ionisation Energy: A Cross-cultural Study

Abstract

Previous studies have indicated that A-level students in the UK and Singapore have difficulty learning the topic of ionisation energy. A two-tier multiple-choice instrument developed in Singapore in an earlier study, the Ionisation Energy Diagnostic Instrument, was administered to A-level students in the UK, advanced placement high school students in the USA, and first-year university students in China, New Zealand and Spain to determine if the students from different countries and educational systems had similar conceptions and difficulties as the students in Singapore with the concepts assessed in the instrument. The results showed that, in general, the students in all six samples had similar alternative conceptions which were grouped under the categories of octet rule framework, stable fully-filled and half-filled sub-shells conceptions and conservation of force thinking. The students also resorted to relation-based thinking when answering items involving the trend of ionisation energies across Period 3. Implications for teaching and further research are discussed.

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Introduction

Ausubel (1968) defines meaningful learning as relating a learning task in a 'nonarbitrary, substantive (non-verbatim) fashion to what the learner already knows' (p. 24), and contrasts meaningful learning with rote learning, which he describes as 'purely arbitrary associations' (p. 24). The degree of meaningfulness of a learning task varies with learners depending on the adequacy of their relevant prior knowledge, so meaningful learning and rote learning is not a dichotomy but rather a continuum (Novak, 1976). The learner's prior knowledge influences the selection and the attention given to the various aspects of the learning task, and he/she needs to retrieve from his/her memory the information necessary to make sense of the task. Taber (2005) describes a typology of learning impediments which was "derived from a consideration of what can go wrong when the prior knowledge 'brought to mind' by a learner does not match the prerequisite learning required to make the intended sense of teaching" (p. 96). He distinguishes between null learning impediments where the learner does not recognize any relevance of the new material to her/his existing knowledge, and substantive learning impediments where the learner distorts the new material in the process of interpreting it through her/his existing knowledge. Null learning impediments can be divided into deficiency impediments where students do not have the required prior knowledge and fragmentation learning impediments where students do not recognize the links between the new material and their existing knowledge. Students usually resort to rote learning if they cannot make sense of the new learning material, especially if the material is required in the

examinations. Knowledge from rote learning tends to become irretrievable from the long-term memory over time, and difficult to apply in new contexts (Novak, 2002), whereas meaningful learning may be readily activated (and so reinforced and consolidated) due to its links with other learning. Novak argues that much of school learning is near the rote learning end of the continuum as it tends to involve "rote learning of concept definitions or statements of principles without opportunities to observe the relevant events or objects, and without careful integration of new concept and proposition meanings" (p. 553).

Substantive learning impediments are often due to the existing alternative conceptions that the students may hold and they include ontological impediments which are spontaneous interpretations of experience, and pedagogic impediments which derive from teaching (Taber, 2005). If students have some prior knowledge but find the new concepts do not fit well with what they already know, they may 'bend' or misinterpret the new concepts to fit their prior knowledge (Johnstone, 2000; Osborne, Bell, & Gilbert, 1983; Taber, 2000) giving rise to alternative conceptions. Teachers, themselves, can be sources of alternative conceptions as they can unwittingly pass their own alternative conceptions to their students. The way they teach, for instance, using vaguely-defined terminology, can also cause misunderstanding (Goodwin, 2000; Lin, Cheng, & Lawrenz, 2000; Soudani, Sivade, Cros, & Medimagh, 2000; Tan, 2005). Textbooks are also not infallible as they can contain errors and misleading illustrations and statements (Boo, 1998; de Posada, 1999; Sanger & Greenbowe, 1999; Wandersee, Mintzes, & Novak, 1994) which cause difficulties for teachers and students using these books.

Studies have shown that students find chemistry difficult as the entities (e.g. atoms, molecules, ions) involved in chemical phenomena and the interactions of these entities are aperceptual (Carr, 1984; Kozma, Chin, Russell, & Marx, 2000 Tsaparlis, 2000). To explain the underlying reaction mechanisms, scientists developed resources such as representations, discourse and tools which "afford certain ways of thinking and talking about underlying entities and processes" (Schank & Kozma, 2002, p. 256). Unfortunately, these resources are mostly inaccessible to students in secondary schools, so the concepts taught in class are "notional, semantic, handed down by authority rather than experienced" (Johnstone, 1999, p. 46), leading to difficulties when students need to shift between the macroscopic, microscopic and symbolic/algebraic representational systems to understand concepts in chemistry and to engage in chemical reasoning (Johnstone, 2000; Nakhleh & Krajcik, 1994; Wu, Krajcik, & Soloway, 2001). Chemistry concepts are also extensively inter-related such that if students have inadequate understanding of the concepts in a particular topic, they are very likely to have difficulty understanding other topics (Ross & Munby, 1991). Thus, it is not surprising that students resort to rote learning or that research has shown that students have null or substantive learning impediments in many chemistry topics such as particulate nature of matter (Krnel, Glazar, & Watson, 2003; Nakhleh & Samarapungavan, 1999; Sanger, 2000; Snir, Smith, & Raz 2003), bonding (Coll & Treagust, 2003; Taber, 1997, 2003a; Tan & Treagust, 1999) and chemical reactions (Johnson, 2000; Solomonidou & Stavridou, 2000; Tan, Goh, Chia, & Treagust, 2002; Van Driel, 2002).

Ionisation Energy

The topic of ionisation energy is usually introduced either in first-year university chemistry courses, or in high school or advanced placement chemistry curriculum studies in many parts of the world, including China, New Zealand, Singapore, Spain, the UK and the USA. The concepts involved in the topic of ionisation energy are important as they also form the bases of the topics of atomic structure, periodic trends and energetics of reactions (Taber, 2003b). Studies in the UK have shown the General Certificate of Education Advanced Level (A-level) students (aged 16-19) found the topic difficult and had alternative conceptions of the principles determining the magnitude of ionisation energy (Taber, 1998a,b, 1999a, 2003b). The students answered questions involving the magnitude of ionisation energy using the octet rule/full shell framework and 'conservation of force' conception, and did not or could not apply basic electrostatic principles that they learned in physics to explain the interactions between the nucleus and electrons in an atom. The octet rule/full shell framework considers the attainment of 'full shells' and/or octets of electrons as a driving force for chemical change, and so uses this as an explanatory principle (e.g. …because atoms 'want' to fill their shells). The conservation of force conception considers the force attracting electrons to a nucleus to be a fixed quantity depending (only) upon nuclear charge, and being distributed between the electrons present in an atom or ion.

As an extension of the UK study on ionisation energy, a two-tier multiple choice diagnostic instrument (Treagust, 1995), the Ionisation Energy Diagnostic Instrument (IEDI) was developed to determine Singapore A-level students' (aged 16-19) understanding of the topic (Tan, Goh, Chia, & Taber, 2005; Tan, Taber, Goh, & Chia, 2005); students in Singapore, similar to students in the UK, first encounter the topic of

ionisation energy in A-level chemistry. Examples of items in the IEDI are given in Appendix A. The items in two-tier multiple-choice diagnostic instruments are specifically designed to identify alternative conceptions and misunderstandings in a limited and clearly defined content area. The first part of each item consists of a multiple-choice content question having usually two or three choices. The second part of each item contains a set of four or five possible reasons for the answer to the first part. Incorrect reasons in the second-tier options are derived from actual student alternative conceptions gathered from the literature and from interviews and free response tests from earlier stages of the development of the instrument. Thus, the second-tier options allow an insight into the underlying reasons for the student's answers, which could not be easily determined in the earlier UK studies.

The Singapore study involved three phases (Tan, Goh, Chia, & Taber, 2005). In the first phase, the content framework of the A-level ionisation energy was defined by a concept map and a list of propositional knowledge statements based on Taber's (1999a) work, an extract of the sections of the A-level chemistry syllabus relevant to ionisation energy (Appendix B), and two chemistry textbooks. The content framework, together with the findings of Taber's (1999a) research, guided the development of the first of three successive free response or justification multiple-choice instruments in which students had to supply reasons for their choice of options in the next phase. The items in the instrument tested students' understanding of the trend of ionisation energies across a period in addition to the factors influencing ionisation energy. The instrument was administered to A-level students and the results obtained facilitated the refinement of the items to produce the second, and subsequently, the third version of the instrument.

Students' alternative conceptions which were identified in the second phase, involving a total of 300 students, were built into the second tier options of the first version of the two-tier multiple choice diagnostic instrument in the third phase. After two trials involving 283 students, the third and final version, the IEDI was developed and administered to 979 students from eight out of a total of seventeen A-level institutions in Singapore in June and July 2003. The results showed that students in Singapore had similar alternative conceptions as the students in the UK in that they employed the octet rule framework and conservation of force thinking to explain the factors influencing ionisation energy. In addition, many students in Singapore used the acquisition of full or half-filled sub-shells as explanatory principles, and also resorted to relation-based reasoning (i.e. reducing a complex situation to a single linear cause and effect) to explain the trend of ionisation energies across Period 3 elements.

Cross-cultural studies of students' alternative conceptions

Diagnostic instruments to assess students' understanding of science concepts are usually developed for a particular educational system in a particular country. However, as established scientific concepts are universal, it is likely that for a given topic at a particular stage of schooling, similar concepts will be taught in schools in different countries. Thus, diagnostic instruments can be administered to students in different educational systems or countries if the content framework of the topic is similar in the educational systems or countries. For example, Goh, Khoo and Chia (1993) administered the two-tier multiple choice diagnostic instrument on covalent bonding and structure developed by Peterson, Treagust and Garnett (1989) to 478 A-level students from seven

A-level institutions in Singapore and found that students in Singapore and Australia had similar alternative conceptions; even the percentages of students holding these alternative conceptions are similar in a number of items in both the Singaporean and Australian samples. Goh et al. argued that the similar results showed the validity and usefulness of such diagnostic instruments. This assertion was reinforced by Birk and Kurtz (1999) who also used the covalent bonding and structure diagnostic instrument in the USA to determine the retention of alternative conceptions over time; the study sought to determine if additional years of chemical education would diminish the alternative conceptions that the students held. Their sample in the cross-age study included high schools students to faculty from US educational institutions, and the alternative conceptions determined were similar to the Australian and Singaporean samples though Birk and Kurtz did not make explicit comparisons with the two previous studies. However, as institutional, cultural and linguistic factors could all feasibly influence the nature of teaching and learning of a topic, it should not be assumed that students in different educational contexts will necessary share the same learning difficulties.

The cross-cultural study on ionisation energy.

In 2004, several chemical education researchers in China, New Zealand, Spain, UK and the USA were approached and agreed to participate in the cross-cultural study to determine if students in different countries and educational systems had similar understanding and alternative conceptions on the topic of ionisation energy. They, in turn, found tertiary chemistry lecturers and high school/A-level teachers who were interested in participating in the study and were able to administer the IEDI to their

students. Thus, convenience sampling was employed, and in 2004, the IEDI was administered to 450 high school and first year university students in five countries. The description of the various samples of students involved is given in Table 1 which includes the Singapore sample as a comparison. The first year university students who participated in the study were from the respective collaborating chemical education researchers' institutions while the high school students were from schools whose teachers responded to invitations to participate in the study. The tertiary chemistry lecturers and high school/A-level teachers involved confirmed that students were taught the concepts in ionisation energy as specified in Appendix B before the IEDI was administered to the students.

Table 1 about here

Several issues arose in the study. Firstly, as convenience sampling was employed and sample sizes were small, the results cannot be assumed to be strictly representative of all first year university students or high school students in the particular country. However, the results can indicate the validity of the IEDI and the feasibility of using the instrument to determine students' conceptions of ionisation energy in countries outside of Singapore where the IEDI was developed. The results suggest whether similar alternative conceptions are common in the different educational contexts, even though the different samples are not from directly equivalent populations in these contexts and are not statistically representative of the populations. Secondly, the instrument had to be

translated from English into Spanish and Chinese before it was administered in Spain and China, and errors could be made in the translation process. However, the Spanish version of the IEDI was thoroughly checked and found to be free of errors by two bilingual tertiary chemistry educators in Spain, and the Chinese version by one bilingual tertiary chemistry educator in China and two bilingual chemistry professors in Singapore. Thirdly, there were two main groups of students involved, high school or A-level students and first year undergraduates. In China, New Zealand and Spain, ionisation energy was taught in high school but first year undergraduates were chosen because of the lecturers involved in the study. The first year undergraduates may have one or two more years of chemical education compared to the high school/A-level students, and the undergraduates are also likely to be, on the average, of higher academic ability than the high school/A-level students as only a percentage of the high school/A-level students qualify for university. It would seem likely that the undergraduates will have a better understanding of ionisation energy and have fewer alternative conceptions compared to high school/A-level students. However, Birk and Kurtz (1999) found in their cross-age study of students' understanding of molecular structure and bonding that the decrease in alternative conceptions over time due to attrition of student population at increasing higher levels of education is less significant than expected; they anticipated a "significant curvature, accelerating with time" (p. 128), but obtained a linear decrease.

Results

Alternative conceptions in this study were considered significant and common if they existed in at least 10% of the students in two or more countries. Table 2 summarises

the significant common alternative conceptions determined from the administration of the IEDI to the students in the six countries. Fourteen significant common alternative conceptions were identified and grouped under the headings of 'Octet rule framework', 'Stable fully-filled or half-filled sub-shells', 'Conservation of force thinking' and 'Relation-based reasoning'. These categories were derived from the results of the earlier Singapore study (Tan, Taber, Goh, & Chia, 2005).

Table 2 about here

Options A4 of item 5, B3 of item 6 and B4 of item 9 (see Table 3) were not considered as alternative conceptions even though they were incorrect. These questions dealt with the trend of ionisation energy across Period 3. In these items, students had to consider which important factors were in play, as well as to decide which factor outweighed the other (nuclear attraction versus shielding/repulsion) in the specific instance. If a student chose one of the stated options, it could indicate that he/she knew which two factors were in play, but decided wrongly the more important factor in that specific situation. Thus, it was difficult to determine if the student had an alternative conception, or if he/she forgot or could not decide which factor outweighed the other in that specific situation. In other words, these errors are better considered failures of recall than lack of understanding of the concepts involved.

Table 3 about here

Octet rule framework

Many students (22-49%) in the six samples thought that the sodium ion would not recombine with an electron to reform the sodium atom because the sodium ion had already achieved a noble gas configuration, and gaining an electron would cause the ion to lose its stability (Item 1, A2). In item 3, a larger percentage of students (40-64%), agreed that the 'sodium ion and a free electron' system was more stable than the sodium atom because the outermost shell of the ion had achieved a stable octet/noble gas configuration (B4). The explicit comparison of the stability of sodium atom with the system consisting of the sodium ion and free electron could have influenced the students' use of the octet rule framework in item 3 compared to item 1. Students also used the octet rule framework to justify why the second ionisation energy of sodium was greater than its first ionisation energy (Item 4, A1, 10-51%). This differs from the curriculum model, which states that the removal of the second electron from sodium involves removing an electron from an inner (second) shell, and this requires more energy as the electrons in the second shell, being closer to the nucleus and less shielded/screened by the two electrons in the first shell, are more strongly attracted to the nucleus.

The octet rule framework was, again, invoked by many students (to a lesser extent in the Singapore and UK samples) in the comparison of ionisation energies of the elements, sodium, magnesium and aluminium. Students believed that the first ionisation energy of sodium was less than that of magnesium and aluminium because the sodium

atom will achieve a stable octet configuration when it loses its valence electron, thus less energy is required to remove the electron (Item 5, B2, 10-36% and Item 7, B2, 11-45%).

Stable fully-filled or half-filled sub-shells

Students in all six samples indicated in item 5 (B1, 13-41%) that magnesium had a higher first ionisation energy than sodium because magnesium had a fully-filled 3s orbital/sub-shell which gave it stability. A smaller percentages of students in four samples chose a similar option in item 6 (A1, 13-30%) as there was a competing relation-based option (Q6, A2, 13-48%). In items 8 (B2, 19-41%) and 9 (A3, 16-51%), students indicated that phosphorus had a higher first ionisation energy compared to silicon and sulphur because the half-filled 3p sub-shell of phosphorus gave it stability. To answer questions on the trends of ionisation energies, students need to remember not only the factors involved (e.g. nuclear charge vs. repulsion/shielding between electrons) but also which factor is more important in a particular situation. Thus, as mentioned earlier, it is here considered less significant if students cannot decide between, for example, A4 or B3 in item 6, or A5 or B4 in item 9. However, it is problematic when students think that a fully-filled 3s sub-shell gives magnesium its stability, and hence higher first ionisation energy compared to aluminum, while phosphorus, with its 3p sub-shell half-filled, is more stable than sulphur, and hence has higher first ionisation energy than sulphur.

Conservation of force thinking

Students indicated in item 2 (A3, 19-54%) that the nuclear attraction would be redistributed among the remaining 10 electrons when an atom of sodium loses an electron

because the number of protons was the same but there was one less electron to attract. Thus, there was 'more' nuclear attraction to be shared by the remaining electrons, so the second ionisation energy of sodium was higher than its first ionisation energy. The curriculum model states that the attraction for an electron by the nucleus depends on the number of protons in the nucleus, the distance of the electron from the nucleus and the shielding effect of other electrons in the atom. Removal of one electron from the sodium atom may reduce some repulsion between electrons causing the remaining 10 electrons to move closer to the nucleus, but there is no 'redistribution' of nuclear attraction among the remaining electrons. In item 4 (A2, 11-21%) students, to a lesser degree, also indicated that the second ionisation energy of sodium was greater than its first because the same number of protons in sodium was attracting 10 electrons now instead of 11.

Relation-based reasoning

As previously mentioned, students needed to remember and understand the factors (nuclear charge, the distance of the electron from the nucleus and the repulsion/screening effect of the other electrons present) which affect the ionisation energy of an atom, the interplay between the factors, as well as remember which factor was more important in a particular situation in order to answer questions on the trends of ionisation energies. However, the results from items 6 and 7 seemed to indicate that some students focused exclusively on one factor which could possibly influence the situation and ignored all others. Driver, Leach, Millar and Scott (1996) describe this type of thinking as relation-based reasoning. Not all samples, for example, the Chinese and the Spanish samples, had significant percentages of students exhibiting relation-based

reasoning. Students from several samples seemed to think that the 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium and sodium (item 6, A2, 13-48%; item 7, A4, 12-28%) because it had more electrons than sodium and magnesium, ignoring the fact that aluminium had a greater nuclear charge than sodium and magnesium. The students in the New Zealand, Singapore, and UK samples who chose A3 in item 7 (20-21%) could also have ignored the greater nuclear charge of aluminium.

Discussion

The octet rule framework was prevalent in all six samples and this could be due to the similar ways in which chemical bonding is taught to students in all six samples. The octet rule is a useful 'rule-of-thumb' (Taber, 2001) when students first learn about chemical bonding because it allows students to determine the number of electrons an atom has to gain, lose or share in order to form a bond with another atom or more than one atom. However, students could "over-generalise the rule from being a way of identifying likely stable species, to become a general purpose explanations for why reactions occur" (Taber, 2001, p. 146) – students who adopt the octet rule framework believe that "chemical reactions take place, and bonds form, to allow atoms to have full outer shells" (Taber, 1999b, p. 136). Teachers and textbook writers might not have clarified the use of the octet rule, or they could also have embraced this alternative conception and transferred it to the students, resulting in the pedagogic learning impediment. Thus, from the octet rule framework perspective, the sodium atom would not be considered as stable as it did not have a full outer shell as compared to the sodium

(Na^+) ion (item 3, B4, 40-69%), so the second ionisation energy of sodium would be higher than its first (item 4, A1, 10-51%), and the sodium ion will not combine with an electron to reform the sodium atom (item 1, A2, 22-49%). Students in the Chinese, US and Spanish samples seemed to choose the octet framework options more often than students in the other samples. However, the percentages for every sample tended to vary to a large extent over the five items (1, 3, 4, 5 and 7), for example, less than 10% in items 5 and 7 to 64% in item 3 for the Singapore sample, because of the presence of other alternative conceptions in the options of each item. Thus, it was difficult to interpret the consistency of students in each sample choosing the octet rule framework option.

The 'stable fully-filled or half-filled sub-shell' thinking was also common in all six samples. Students could have 'derived' the 'stable fully-filled or half-filled sub-shell' thinking (e.g. item 5, B1, 13-41% and item 8, B2, 19-41%) from their existing octet rule framework as both seemed to involve similar reasoning – completeness or symmetry gives rise to stability (Taber & Tan, 2006); it seemed to lead 'naturally', without any apparent conflict, from full shell to full sub-shell, and then to half-filled sub-shell.

It needs to be noted that teachers and textbooks might also have used 'stable fully-filled or half-filled sub-shell' to explain the anomaly in the ionisation energy trend across Periods 2 and 3 of the Period Table and to help students remember the anomaly (Cann, 2000; Tan, Taber, Goh, & Chia, 2005), a situation similar to the octet rule. Therefore, the teachers' and textbooks' use of 'stable fully-filled or half-filled sub-shell' could have given additional credibility to this substantive learning impediment, so it was not surprising that a significant percentage of students exhibited the alternative conception when answering questions on the trends of ionisation energies. The percentages of

students choosing the 'stable fully-filled or half-filled sub-shell' in the four items (5, 6, 8 and 9) indicated that more Chinese and New Zealand students were attracted this option than students in the other samples. There seemed to be some consistency shown by the Chinese sample as high percentages of students were also attracted to the related octet rule framework options.

The percentages of students in all samples choosing the conservation of force option in item 4 (A2, 11-21%) are less than in item 2 (A3, 19-54%) because of the competing octet rule option in item 4 (A1, 10-51%). Though conceptually incorrect, the conservation of force thinking "does often allow correct predictions to be made (successive ionisation energies do increase) and seems to have an intuitive attraction to many students" (Taber, 2003b, p. 156); it is highly likely that students in all samples are used to the concept of sharing in their everyday lives, and in general, less recipients means bigger portions. Thus, it would require little effort for some of them to reason that fewer electrons would mean greater nuclear attraction for the remaining electrons (Taber & Tan, 2006). Higher percentages of students in the US, New Zealand and Singapore samples were attracted the conservation of force thinking options compared to the students in the other samples.

Students' use of relation-based reasoning seemed to indicate that they have difficulty in coordinating the different factors influencing the trend of ionisation energy across Period 3 and/or did not appreciate how a change in one factor might be cancelled or overcompensated by the co-variation in another (Taber & Tan, 2006; Tan, Taber, Goh, & Chia, 2005). For example, some students might have focussed on the increased repulsion between the electrons in the aluminium atom because it had more electrons

compared to the sodium and magnesium atoms but did not consider that aluminium also had a higher nuclear charge as well as the interplay between nuclear charge and repulsion/screening effect. Their search for an answer seemed to stop when they identified a possible factor and this could be due to their experience in class where teachers do not usually explicitly discuss all the factors involved and how they interacted with each other, but instead referred only to the predominant factor in the given situation.

The students in the Chinese sample, and to a lesser extent, the Spanish sample did not find relation-based thinking options in items 6 and 7 attractive compared to the other options; less than 10% of students in the Chinese sample chose these options. For example, in item 6, the students in the Chinese sample were more attracted to the 'stable completely-filled 3s sub-shell of magnesium' option (A1, 30%) and option B3 (37%) where it was stated that magnesium had a lower first ionisation energy compared to aluminium because of the effect of an increase in the nuclear charge of aluminium was greater than the repulsion between the electrons in its outermost shell. In item 7, the octet rule framework option (B2, 45%) proved more attractive to the Spanish sample than the relation-based thinking option, and 30% of the students in the Chinese sample chose option B3 in which the first tier option did not agree with the second tier option.

Implications for teaching and research

It was suggested in an earlier section that students most likely acquired the octet rule framework during the learning of bonding during earlier secondary education, and this might have been encouraged by teachers using anthropomorphic language (Coll & Treagust, 2002; Taber & Watt, 1996) such as atoms 'wanting' complete shells that may

imply that these shells have an inherent stability (Tan, Taber, Goh, & Chia, 2005); a similar situation might have occurred with 'stable fully-filled sub-shells and half-filled sub-shells'. Thus, teachers need to be careful with their use of anthropomorphic language when discussing ionisation energy. When they spot students demonstrating this thinking, teachers should ask students to rephrase their explanation in more technical language. If the students are unable to do so, the teacher should model an explanation using the appropriate scientifically valid ideas. Teachers should also emphasise that "stability is a relative term which only becomes meaningful in a particular context", pointing out that as "ionisation energy is defined in terms of isolated atoms and so judgements of stability need to consider how stable the ion is compared with the atom in the absence of the net electrostatic field of a metallic lattice, a solvent sheath of water molecules or a surrounding set of counter-ions" (Taber, 2003b, p. 163).

To challenge the common notion that the nucleus gives out an amount of force or attraction to be shared by the electrons, teachers need to emphasize the basic Coulombic principles. A possible analogy to teach the nuclear attraction for an electron is to say that it is similar to the heat one receives from a bonfire - this is dependent on how big the bonfire is, the distance one is away from the bonfire and whether one is blocked (screened/shielded) from the bonfire, but is independent of how many people are present at the same distance away from the bonfire. This analogy may prevent students from thinking that electrons 'share' the attraction from the nucleus. However, it does not take into account the equal and mutual attraction of the nucleus and the electron, as well as the repulsion between electrons, so this has to be highlighted.

Many students in the New Zealand, Singapore, UK and US samples used relation-based thinking to explain the trend of first ionisation energy of the Period 3 elements. The students seemed to be aware of a range of potentially relevant factors that can influence ionisation energy but seemed to focus only on one apparently relevant factor and apply it on the assumption that all other potential factors are held constant (Tan, Taber, Goh, & Chia, 2005). Thus, they may notice that a phosphorus atom has one more electron than a silicon atom but not consider that it also has one more proton in its nucleus. Teachers should be always state explicitly all the factors involved when discussing ionisation energy and making comparisons, and how these factors come into play in a particular situation. There are situations when some factors can be ignored, other situations where different factors have effects in the same direction, and sometimes they work in opposite directions, so there is some degree of compensation – in this case a student can decide on the dominant factor(s) only by looking at the experimental data.

The results showed that, in general, students in the six samples had similar alternative conceptions, albeit to different degrees. To the extent that the science is universal, and human cognitive characteristics shared across different populations, we might well expect similar findings. Yet differences in curriculum, teaching sequences, and teaching approaches might sometimes be important factors in whether students learn the intended target knowledge. Similarly, as many alternative conceptions derive in part from linguistic cues, or from 'life-world' or 'folk' science, there is considerable potential for cultural differences to influence learning, especially where different languages are used for instruction. This study should be seen as part of a broader programme to examine how differences in teaching and learning in different educational contexts lead

to differences in typical understandings of ionisation energy. The next step is to interview students in the various countries to probe their understanding behind their answers. Their teachers' conceptions of ionisation energy and the way they teach ionisation energy also have to be examined to determine how they influence their students' learrning of ionisation energy. Similarly, analysis of textbooks and other curriculum material used in the various countries could also yield commonalities and differences in the way ionisation energy is presented to students and aspects of the material which could create difficulty for students to understand concepts in ionisation energy.

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Appendix A

Examples of items from the Ionisation Energy Diagnostic Instrument

Sodium atoms are ionised to form sodium ions as follows:

$Na(g) \rightarrow Na^{+}(g) + e$

1. Once the outermost electron is removed from the sodium atom forming the sodium ion (Na^{+}), the sodium ion will not combine with an electron to reform the sodium atom.

   A True.

   B False.

   C I do not know the answer.

   Reason:

   (1) Sodium is strongly electropositive, so it only loses electrons.

   (2) The Na^{+} ion has a stable/noble gas configuration, so it will not gain an electron to lose its stability.

   (3) The positively-charged Na^{+} ion can attract a negatively-charged electron.

2. When an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons in the sodium ion (Na^+).

A True.

B False.

C I do not know the answer.

Reason:

(1) The amount of attraction between an electron and the nucleus depends on the number of protons present in the nucleus and the distance of the electron from the nucleus. It does not depend on how many other electrons are present, although electrons do repel each other (and can shield one another from the nucleus)

(2) The electron which is removed will take away the attraction of the nucleus with it when it leaves the atom.

(3) The number of protons in the nucleus is the same but there is one less electron to attract, so the remaining 10 electrons will experience greater attraction by the nucleus.

3. The Na(g) atom is a more stable system than the Na^+(g) ion and a free electron.

A True.

B False.

C I do not know the answer.

Reason:

(1) The Na(g) atom is neutral and energy is required to ionise the Na(g) atom to form the Na^+ (g) ion.

(2) Average force of attraction by the nucleus on each electron of Na^+ (g) ion is greater than that of Na(g) atom.

(3) The Na^+(g) ion has a vacant shell which can be filled by electrons from other atoms to form a compound.

(4) The outermost shell of Na^+(g) ion has achieved a stable octet/noble gas configuration.

5. Sodium, magnesium and aluminium are in Period 3. How would you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$)?

A. The first ionisation energy of sodium is greater than that of magnesium

B. The first ionisation energy of sodium is less than that of magnesium.

C. I do not know the answer.

Reason:

(1) Magnesium has a fully-filled 3s sub-shell which gives it stability.

(2) Sodium will achieve a stable octet configuration if an electron is removed.

(3) In this situation, the effect of an increase in nuclear charge in magnesium is greater than the repulsion between its paired electrons in the 3s orbital.

(4) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, and this effect is greater than the increase in the nuclear charge in magnesium.

(5) The 3s electrons of magnesium are further from the nucleus compared to those of sodium.

6. How do you expect the first ionisation energy of magnesium ($1s^2\ 2s^2\ 2p^6\ 3s^2$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?

A. The first ionisation energy of magnesium is greater than that of aluminium.

B. The first ionisation energy of magnesium is less than that of aluminium.

C. I do not know the answer.

Reason

(1) Removal of an electron will disrupt the stable completely-filled 3s sub-shell of magnesium.

(2) The 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium.

(3) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the repulsion between the electrons in its outermost shell.

(4) In this situation, the effect of an increase in nuclear charge in aluminium is less than the repulsion between the electrons in its outermost shell.

(5) The paired electrons in the 3s orbital of magnesium experience repulsion from each other, whereas the 3p electron of aluminium is unpaired.

7. How do you expect the first ionisation energy of sodium ($1s^2\ 2s^2\ 2p^6\ 3s^1$) to compare to that of aluminium ($1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$)?

A. The first ionisation energy of sodium is greater than that of aluminium.

B. The first ionisation energy of sodium is less than that of aluminium.

C. I do not know the answer.

Reason

(1) Aluminium will attain a fully-filled 3s sub-shell if an electron is removed.

(2) Sodium will achieve a stable octet configuration if an electron is removed.

(3) The 3p electron of aluminium experiences greater shielding from the nucleus compared to the 3s electron of sodium.

(4) The 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium.

(5) In this situation, the effect of an increase in nuclear charge in aluminium is greater than the shielding of the 3p electron by the 3s electrons.

Appendix B

Assessment objectives on ionisation energy in the A-level syllabus for 2001

Atomic structure

1. Explain the factors influencing the ionisation energies of elements.
2. Explain trends in ionisation energy across a period and down a group of the Periodic Table.
3. Deduce the electronic configurations of elements from successive ionisation energy data.
4. Interpret successive ionisation energy data of an element in terms of the position of that element within the Periodic Table.

Chemical energetics

Apply Hess' Law to construct simple energy cycles, e.g., Born-Haber cycle, and carry out calculations involving such cycles and relevant energy terms (including ionisation energy and electron affinity).

The periodic table: Chemical periodicity

Periodicity of physical properties of the elements: variation with proton number across the third period (sodium to argon)

1. Explain the variation in first ionisation energy.
2. Deduce the nature, possible position in the Periodic Table, and identity of unknown elements from given information of physical and chemical properties.

Table 1. Samples of the students involved in the study

Country	No. of students	Description of students
UK	111	A-level students (aged 16-19) from five schools.
Spain	104	First year undergraduates (aged 19-21) from one university.
China	71	First year undergraduates (aged 19-21) from one university.
New Zealand	121	First year undergraduates (aged 19-20) from one university.
USA	43	Advanced placement high school students (aged 16-18) from four schools.
Singapore	979	A-level students (aged 16-19) from eight schools.

Table 2. Alternative conceptions determined from the administration of the IEDI

Alternative conception	Ch	NZ	Sp	UK	US	Ex sg	Sg	All
Octet rule framework								
1. The sodium ion will not recombine with an electron to reform the sodium atom as its stable octet configuration would be disrupted. (*Q1, A2)*	31[1]	22	49	27	44	33	44	40[2]
2. The Na(g) atom is a less stable system than the Na^+(g) and a free electron because the Na^+(g) has a stable octet configuration. *(Q3, B4)*	69	49	40	51	63	52	64	60
3. The second ionisation energy of sodium is higher than its first because the stable octet would be disrupted. *(Q4, A1)*	51	27	10	16	40	25	16	19
4. The first ionisation energy of sodium is less than that of magnesium because sodium will have achieved a stable octet configuration if an electron is removed. *(Q5, B2)*	16	10	36	11	21	18	-	12
5. The first ionisation energy of sodium is less than that of aluminium because sodium will achieve a stable octet configuration if an electron is removed *(Q7, B2)*	11	11	45	-	30	20	-	10
Stable fully-filled or half-filled sub-shells								
1. The first ionisation energy of sodium is less than that of magnesium because magnesium has a fully-filled 3s sub-shell. *(Q5, B1)*	28	41	25	22	30	29	13	18
2. The first ionisation energy of magnesium is greater than that of aluminium because removal of an electron will	30	19	-	13	19	16	-	-

disrupt the stable completely-filled 3s sub-shell of magnesium. *(Q6, A1)*								
3. The first ionisation energy of silicon is less than that of phosphorus because the 3p sub-shell of phosphorus is half-filled. *(Q8, B2)*	41	40	38	23	19	33	25	28
4. The first ionisation energy of phosphorus is greater than that of sulphur because the 3p sub-shell of phosphorus is half-filled, hence it is stable. *(Q9, A3)*	51	35	-	30	16	28	20	22
Conservation of force thinking								
1. When an electron is removed from the sodium atom, the attraction of the nucleus for the 'lost' electron will be redistributed among the remaining electrons in the sodium ion. *(Q2, A3)*	24	50	19	43	54	38	50	46
2. The second ionisation energy of sodium is greater than its first ionisation energy because the same number of protons in the Na^+ ion attracts one less electron, so the attraction for the remaining electrons is stronger. *(Q4, A2)*	18	18	11	14	21	16	18	17
Relation-based reasoning								
1. The first ionisation energy of magnesium is greater than that of aluminium because the 3p electron of aluminium is further from the nucleus compared to the 3s electrons of magnesium. *(Q6, A2)*	-	26	13	39	37	24	48	41
2. The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium experiences greater shielding from the nucleus compared	-	21	-	20	-	12	21	18

to the 3s electron of sodium. *(Q7, A3)*								
3. The first ionisation energy of sodium is greater than that of aluminium because the 3p electron of aluminium is further away from the nucleus compared to the 3s electron of sodium. *(Q7, A4)*	-	12	-	21	28	12	24	21

Note: Sp represents the Spanish sample

Ch represents the Chinese sample

NZ represents the New Zealand sample

Sg represents the Singapore sample

Ex sg represents the all sample excluding the Singapore sample

All represents all samples from the six countries.

- indicates that the figure is below 10%

[1] Figures are percentages.

[2] The overall figures will be skewed by the large Singapore sample, hence this category was not included in the discussion of the results.

Table 3. Significant errors of students (10% or greater), which were not considered as alternative conceptions

Errors	UK	Sp	Ch	NZ	US	Exsg	Sg	All
The first ionisation energy of sodium is greater than that of magnesium because the paired electrons in the 3s orbital of magnesium experience repulsion from each other and this effect is greater than the increase in the nuclear charge in magnesium. *(Q5, A4)*	10	-	-	-	-	-	22	16
The first ionisation energy of aluminium is greater than that of magnesium because the effect of an increase in nuclear charge in aluminium is greater than the repulsion between the electrons in its outermost shell. *(Q6, B3)*	13	22	37	10	-	18	-	11
The first ionisation energy of phosphorus is less than that of sulphur because the effect of an increase in nuclear charge in sulphur is greater than the repulsion between its 3p electrons. *(Q9, B4)*	17	20	18	-	19	15	10	12