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Student conceptions of ionic bonding: patterns of thinking across three European contexts

Abstract

Previous research has reported that students commonly develop alternative conceptions in the core topic of chemical bonding. Research in England has reported that students there commonly demonstrate an alternative 'molecular' conceptual framework for thinking about ionic bonding: in terms of the formation of molecule-like ions pairs through electron transfer, which are internally bonded, but not bonded to other ions. The present study reports the use of translated versions of a diagnostic instrument to elicit the conceptions of bonding in NaCl (commonly used as the teaching example of an ionic compound) from two samples of students setting out on university courses in Greece and Turkey. The study reports that students in these two contexts displayed high levels of support for statements based upon the alternative conceptual framework identified in the English context. Students commonly develop similar alternative conceptions of ionic bonding in these three different educational contexts. The study also found some quite large differences in the specific response patterns across these three contexts, some of which could reflect specific features of the different curriculum contexts. The study reinforces the cross-national nature of the challenge of effectively teaching the abstract models of chemistry at the submicroscopic level. It also provides intriguing suggestions that close study of the interactions between specific curriculum contexts and specific patterns in students thinking offers much potential for identifying particular aspects of subject pedagogy that either support or impede the learning of accepted scientific models.

Key terms: ionic bonding; learning chemistry concepts; alternative conceptions; conceptual frameworks; cross-national comparisons; cultural factors in learning

Introduction

Students in two European countries, Greece and Turkey, completed a diagnostic instrument designed to elicit thinking related to an alternative conceptual framework that had been identified from an interview study in a third educational context, England. The same diagnostic items had previously been used to survey a sample of students in that context. This study, then, offers an opportunity to compare responses across three educational contexts to explore the extent of similarity in students adopting the alternative conceptual framework.

It is considered valuable to carry out such comparisons, because the development of alternative conceptions can be influenced by a range of factors – e.g. intuitive responses to everyday phenomena (diSessa, 1993; Taber & García Franco, 2010); folk-science notions that have common currency in the 'life-world' of everyday life (Claxton, 1993; Solomon, 1993); interpretation of linguistic cues (Schmidt, 1991); aspects of the specific teaching models and approaches adopted (Taber, 2003) – which are likely to interact in a range of ways. Understanding how to improve pedagogy to reduce the uptake of alternative conceptions is therefore a challenge to researchers. One 'natural experiment' is to compare learning outcomes in different educational systems where institutional features (curriculum, pedagogy) and language of instruction vary. Such comparisons can in principle at least offer some guidance on the extent to which common alternative conceptions derive from factors intrinsic to the scientific concept and human cognition, rather than peculiarities of particular ways of presenting and explaining the science (Taber, 2009).

Ionic bonding as a topic in chemical education

Chemical bonding has long been recognised as one of the core concept areas in chemistry education (Fensham, 1975). As a science, chemistry makes extensive use of models that explain chemical phenomena in terms of the properties of submicroscopic particles such as atoms, ion and molecules (Gilbert & Treagust, 2009; Jensen, 1995; Johnstone, 2000). Understanding the ways in which these entities can be linked (i.e. the nature of bonding) is central to both appreciating material structures, and to developing explanatory schemes for chemical processes. Chemical science has developed a wide range of bonding models, drawing upon a small number of core approaches (e.g. valence bond and molecular orbital), and these models differ in their degree of sophistication, and so their ranges of application.

In understanding material properties it is common to consider four main models of bonding as primarily responsible for holding the submicroscopic particles together: covalent bonds (for example, in diamond); ionic bonding (for example, in common salt, NaCl); metallic bonding (for example, in copper); and intermolecular bonding (for example, binding the molecules together in ice or in sulphur crystals). Such a typology is inevitably a gross simplification. For example the intermolecular bonding in ice is considered to be of a different type (directional hydrogen bonding) to that in sulphur (van der Waals' forces, i.e. induced-dipole – induce-dipole interactions). Moreover, ionic, covalent and metallic bonding models are best considered to reflect 'ideal cases' with most real substances being understood as having bonding intermediate between these forms. Nonetheless, the utility of this classification is sufficient for it be considered valuable to teach basic models of covalent, ionic and metallic bonding in senior school science in many countries.

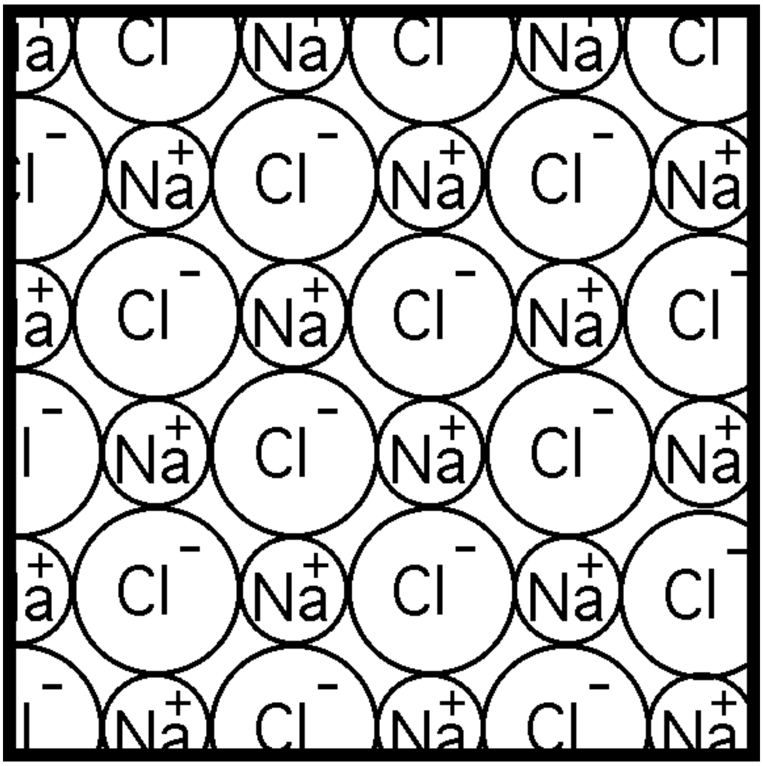

Figure 1. Two-dimensional representation of the NaCl structure

Ionic bonding is the form of chemical bonding associated with salts, that is compounds that form between elements with strong electronegative differences, such as sodium (an electropositive metallic element) and chlorine (an electronegative nonmetallic element). Substances considered to have ionic bonding tend to be hard solids, which form crystals tending to cleave along planes, have high melting temperatures, and are sometimes fairly or very soluble in polar solvents such as water, whilst generally having very low solubility in organic solvents such as hydrocarbons. These properties are explained in terms of the submicroscopic structure being an extended three-dimensional lattice of charged ions. In the case of sodium chloride, NaCl, the lattice is considered to consist of alternating Na^+ and Cl^- ions, each surrounded by six counter-ions in an octahedral arrangement. A simple representation of part of one layer of the NaCl structure is shown in figure 1. As Gillespie (1997, p. 862) has noted, "all chemical bonds are formed by electrostatic attractions between positively charged cores and negatively charged valence electrons. Electrostatic forces are the only important force in chemistry…We can simply describe ionic bonds as resulting from the electrostatic attraction between ions".

Student thinking about ionic bonding

One of the widely recognised problems of teaching and learning chemistry is that the observable bench phenomena that students can perceive directly are largely explained in terms of 'particle models' (Gilbert & Treagust, 2009; Harrison & Treagust, 2002; Jensen, 1995; Johnstone, 1991). These are models of the conjectured nature and structure of matter at sub-microscopic levels, beyond any direct observation. The 'particles' of these models – ions, molecules, electrons, atoms etc - are not like the particles of material, such as specks and grains, familiar to students. Rather they are a distinct type of entity (they have been labelled as 'quanticles') being 'fuzzy' in 'fading away' rather than having definite surfaces, following quantum rules, and having wave as well as particle aspects.

Students are commonly introduced to a basic particle model (i.e. that all substances are constructed of tiny particles – not yet discriminating between molecules, atoms, etc.) to explain the states of matter and changes of state, around the start of secondary education, e.g. c.11 years of age. Whilst some pupils at this age or younger may well be ready to tackle such ideas (Georgousi, Kampourakis, & Tsaparlis, 2001), most students at this age usually show limited ability to cope with highly abstract notions (Kreitler & Kreitler, 1989; Shayer & Adey, 1981), and research has suggested that understanding of these ideas is often limited at this age (Johnson, 1998). Understandably, students commonly make sense of these ideas by assuming teachers are talking about something like (if not actually) salt or sand grains, but perhaps somewhat smaller.

This is inherently problematic in learning chemistry, as a key feature of the chemists' explanatory schemes is that the macroscopic properties and behaviour of substances can be explained by the very different properties of the quanticles. Yet in the absence of an appreciation of the nature of the quantum world, students commonly develop an alternative, almost tautological, alternative explanatory scheme – that a material is yellow or soft or cubic or whatever, because it is composed of particles that are yellow or soft or cubic etc. (Ben-Zvi, Bat-Sheva, & Silberstein, 1986; Brook, Briggs, & Driver, 1984). Such explanations, as well as being inaccurate, simply relocate what is to be explained at a different scale, whilst giving an impression of offering explanatory value (Taber, 2001a).

Having been introduced to an undifferentiated particle theory early in secondary education, students are usually, within a few years, expected to learn about ions and molecules and to understand them, and their role as the components of substances, based upon a simple model of atomic structure. However, research suggests that for most pupils, a clear understanding of the basic level particle model may only develop over an extended period of time (Johnson, 1998, 2005). Consequently it is not surprising that research has found that student learning about chemical bonding (i.e. the interactions between quanticles) is also problematic, and students commonly present alternative conceptions of chemical bonding concepts (Levy Nahum, Mamlok-Naaman, Hofstein, & Taber, 2010; Özmen, 2004; Postholm, 2010; Taber, 1998; Taber & Coll, 2002).

Butts and Smith (1987) undertook research to follow up a survey finding that *the difference in properties between ionic compounds and molecular compounds* had been rated as a difficult topic by 29% of students asked. Butts and Smith interviewed 26 Australian high school chemistry students about this topic. Ten of the students referred to *molecules* of NaCl (p.196) and four of the students interviewed actually proposed either that the 'NaCl molecules' had internal covalent bonds, but were ionically bonded to other molecules, or *vice versa* (p. 196). Butts and Smith reported that one student interpreted the 'sticks' around the 'balls' in a common form of model used to illustrate NaCl structure in chemistry teaching as "one ionic bond and five physical bonds", whilst another "would have expected seven wires not six, because chlorine has seven electrons in its outer shell".

In an interview study exploring developing thinking about bonding among students studying in an English further education college (16-19 year olds, studying a what is known as 'Advanced' level or A-level), Taber found that students demonstrated ideas about ionic bonding similar to those found by Butts and Smith. Taber used a series of simple line diagrams as foci in his interview, following the protocol known as 'interviews about instances' (Gilbert, Watts, & Osborne, 1985). One of the focal images use, is reproduced in figure 2.

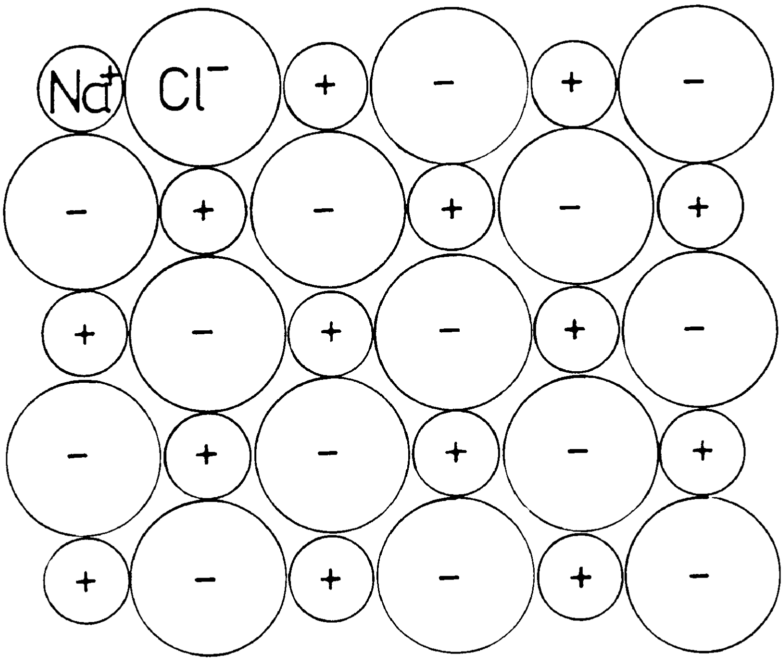

Figure 2: the focal figure presented in the diagnostic instrument

Taber proposed an alternative 'molecular' framework for making sense of ionic bonding, that as well as including molecular or pseudo-molecular entities encompassed three particular alternative conceptions elicited in interviews (Taber, 1994):

- that an ionic bond only existed where there had been an electron transfer between atoms to form ions;
- that electrovalency (charge) limited the number of ionic bonds formed;
- that the ionic lattice comprised of ions that were ionically bonded to some counter-ions, and attracted by other by 'just forces'

The sense of conceptual framework used here follows Gilbert and Watts (1983, p. 69) who used this term to mean "generalised non-individual descriptions… thematic interpretations of data, stylised, mild caricatures of the responses made by students", rather than accounts of the thinking of specific individuals.

In the example of NaCl, a student would typically consider a Na^+ ion to be *bonded* to a single Cl^- ion by an ionic bond, and then *attracted* to another 5 because of the electrical forces between oppositely charged ions. That is, the ionic bond was considered to be something *more than* the electrical attraction; and this was because it was associated in the student's mind with a conjectured electron transfer event during which ions were formed to allow the atoms to obtain octet structures/full outer shells. The consequence of this way of thinking is that particular ion pairs in the NaCl ionic lattice are considered to be to some extent discrete units: if not molecules (cf. Butts & Smith, 1987), then certainly something akin to this.

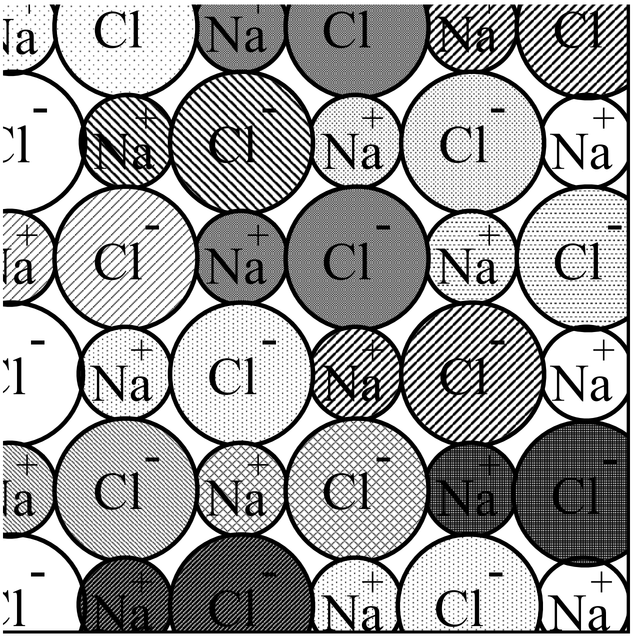

Figure 3: Perceiving the ionic lattice in terms of ion-pairs undermines the symmetry of the interactions between neighbouring ions

In Taber's interview study, he found that when some students were shown an image such as figure 2, they would be able to indicate which ions (they imagined) were paired in this way. The cue of fully labelling one cation and one anion seemed to initiate 'symmetry breaking', and allow the students to then pair off the ions shown (this is represented with shading in figure 3 – which represents how many students conceptualise representations such as figure 2).

For these English students, the focus of ionic bonding was an electron transfer event, presumably deriving from teaching models where ion formation (from individual discrete atoms) is represented in terms of an electron transfer event from a Na atom to a Cl atom. This teaching model reflects an energetically unfavourable process, and has little relevance to how sodium chloride might be formed in authentic chemical contexts (e.g., direct combination; acid–base neutralisation). However, the notion that ionic bonds are formed by an electron transfer between atoms seems to be one that students readily accept and adopt: so, for example, students asked about precipitation reactions have been found to explain ionic charge in a precipitate as due to electron transfer between the species present in the precipitate, even after acknowledging those same ions were already present in the reagent solutions (Taber, 2002b).

Taber suggested that English students' thinking about ionic bonding fitted into a broader conceptual framework that students commonly adopted when thinking about chemical bonding, chemical reactions and other related topics (for example, patterns in ionisation energies), deriving from a core explanatory principle that atoms 'wanted' or 'needed' to fill their shells (Taber, 1998).

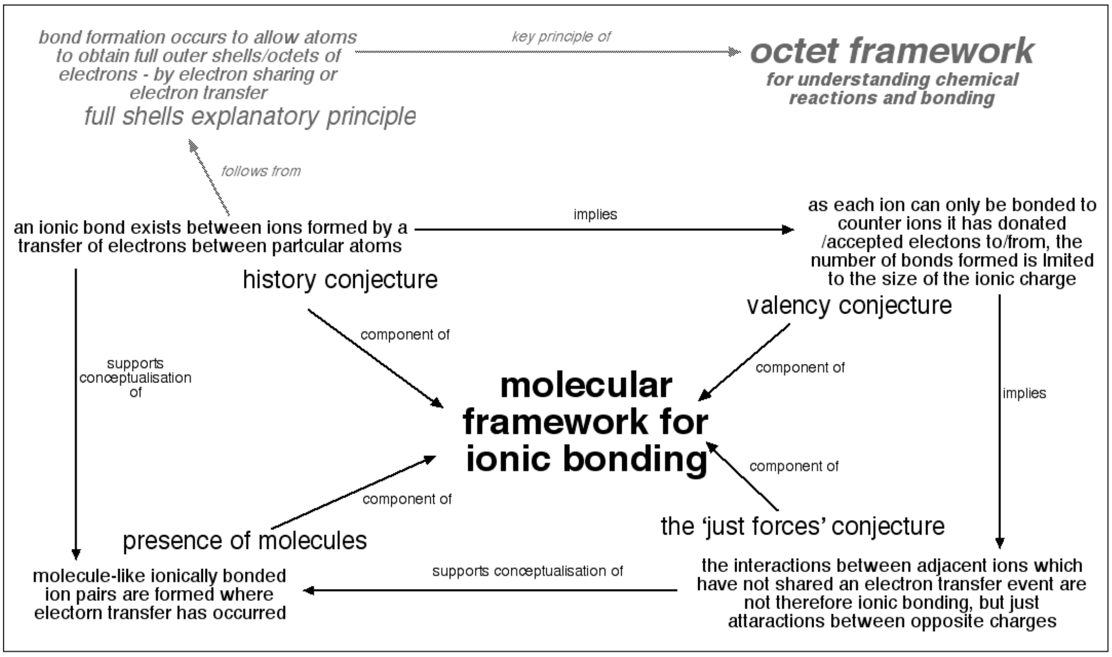

Figure 4: An alternative conceptual framework for ionic bonding
representing thinking of English college students

A simple pencil-and-paper questionnaire developed from students' comments elicited in Taber's interview study was prepared as a diagnostic instrument. (This is discussed in more detail below.) A survey of English students near the end of school science (14-16 year olds) and undertaking A-level study (16-19 year olds) suggested that students were commonly supportive of statements reflecting the molecular framework, but often *also* agreed with statements reflecting the curriculum model (i.e. that all adjacent oppositely charged ions are ionically bonded together). Taber suggested that students often operated with a mixture of the alternative conceptual framework and the curriculum model (Taber, 1997), which appeared to reflect the slow progression toward more chemically acceptable understanding during advanced study (Taber, 2001c).

Some aspects of the alternative 'molecular' conceptual framework describing the ideas elicited from English students have been reported in research from other educational contexts. Coll and Taylor (2002) reported students from Australasia associating ionic bonding with electron transfer. They reported one secondary student describing ionic bonding as "where they donate electrons and receive electrons" (p.179), and a sodium atom that 'prefers' to lose an electron (p.180).

Coll and Treagust also reported a study where students from Aeotora/New Zealand at three educational levels – secondary school, undergraduate and graduate - were interviewed about their mental models of bonding (Coll & Treagust, 2003). They reported that "the secondary school learners identified ionic bonding as an attraction between charged species" but " related their mental models directly to the octet rule of full-shell stability" (p. 472). So although the bond was understood in terms of "attraction between oppositely charged species", the octet rule was seen as the "sole driving force" for bonding, leading to a transfer of electrons as an "automatic consequence" (p. 478). Some of the secondary school students considered salt structures to be "molecular in nature" (p. 475). Coll and Treagust reported that even "the graduates related the formation of ions to the octet rule", and they quoted one of these graduate students describing in anthropomorphic terms how "the sodium prefers to have a one plus and the chlorine prefers to have a one minus" (p. 474).

Mendonça and Justi (2010) report a case study of an innovative, modelling-based, approach to teaching 16-18 year-olds about ionic bonding in Brazil. Despite considerable success in encouraging students to think about bonding in electronic terms, and despite explicit study of the energetics of ion formation, it was found that some of the students "related the NaCl stability to the formation of valence octets, which, for them, justified the energy released" (p.494) in a post-test.

Elsewhere, in a review of student answers on the Israeli matriculation examination taken by 17-18 year olds, Levy Nahum and colleagues (Levy Nahum, Hofstein, Mamlok-Naaman, & Bar-Dov, 2004) found examples of references to sodium chloride consisting of two ions, and comparisons of the strength of forces between *molecules* in sodium chloride and potassium iodide. In a study undertaken with Turkish Year 11 students, Ünal and colleagues (Ünal, Coştu, & Ayas, 2010) reported students talking about ionic bonds in terms of electron transfer, and one of the interviewees they quote explicitly referred to how this would form a molecule.

Development of a simple objective instrument

The 'truth about ionic bonding' diagnostic instrument was designed as a simple pencil-and-paper instrument that would allow ready investigation of learners' thinking about ionic bonding. The instrument consisted of a simple line diagram representing an ionic structure (see figure 2), and thirty statements which students were asked to judge as 'true' or 'false'. Respondents were given a simple response sheet allowing them to select the 'true', 'do not know' or 'false' response for each item.

The thirty items were designed to include statements that reflected both the formal curriculum model, the electrostatic framework for understanding ionic bonding; as well as statements reflecting the alternative, molecular framework. The latter statements were informed by the comments of students in Taber's interview study (see above) and reflected different components of the framework: the presence of molecules in the lattice; the 'history conjecture' (that ionic bonds were found where an electron transfer had occurred); the consequent 'valency conjecture' (that ions could only form as many bonds as the number of electrons donated or accepted); and the 'just forces' conjecture (that where adjacent counter ions has not been involved in an electron transfer event, they were attracted, but only by forces, not a bond).

After piloting in a further education college, the instrument was administered to students in a range of English institutions. The respondents made up a convenience sample, where teachers responding to a short item in the practitioners' periodical *Education in Science*, offered to administer the instrument with their classes. Copies of the instrument were provided by Taber through the post, and completed response sheets were returned to Taber for analysis. Analysis simply comprised of tallying the number of students giving each response category in each class. A small proportion of responses were missing or ambiguous, but in the vast majority of cases students clearly indicated one response category for each item (Taber, 1997).

The data from 370 students in 8 institutions (schools and colleges) was combined into three subcategories reflecting (a) school-age (i.e. c.15-16 year olds) students who had studied the topic of ionic bonding to school leaving level (157 students); (b) students taking A level chemistry in post-compulsory education, but not having yet studied the topic further at this level (84 students); (c) students taking A level chemistry in post-compulsory classes, and having studied the topic further at this more advanced level (129 students). High levels of agreement with statements based on the alternative conceptual framework were found, with only a modest decline across subsamples (a) – (c). The findings were reported (Taber, 1997), and these published results will be drawn upon for comparison with the data collected from the two new samples reported below.

Refinement of the instrument

As part of a programme of developing teacher classroom resources (Murphy, Jones, & Lunn, 2004), the UK Royal Society of Chemistry sponsored a project during 2000-2001 to develop materials to support teachers in challenging students' alternative conceptions in chemistry (Taber, 2001b). As part of this project a range of classroom diagnostic tools were prepared (Taber, 2002a). Some of these were developed especially for the project, and some were based on existing instruments. The 'truth about ionic bonding' instrument was evaluated as a classroom tool, and as a result of feedback from classroom teachers, a reduced 20-item version was included in the published classroom resources. A minor change of wording in one item was made - item 20 (which was item 29 of the original instrument), 'there are no molecules in the diagram' was modified to 'there are no molecules shown in the diagram'. It was the refined 20-item version of the instrument that was used in the Greek and Turkish studies reported here. Two versions of the instrument were published, offering respondents a choice of two (true/false) or three (true/do not know/false) response options, as some teachers preferred a 'forced-choice' version of the instrument.

Investigating student thinking in three educational contexts

The aims of the present study relate to two research questions:

- Does the Truth about Ionic Bonding Diagnostic Instrument suggest that students in Greece and Turkey acquire the alternative conceptions about ionic bonding found in the earlier interview study in England?
- Are there any patterns in the national profiles of responses to the Truth about Ionic Bonding Diagnostic Instrument that could suggest that differences between the three

different cultural and educational contexts influence the way students come to understand the ionic bond concept?

The original context of the research was England, at a time when a National Curriculum for science was about to be introduced for the compulsory school years (i.e. ages 5-16), setting out target knowledge to be taught. By the end of secondary schooling, students were expected to have learnt some basic ideas about chemical bonding, *i.e.,*

- that new substances are formed when atoms combine
- that chemical bonding can be explained in terms of the transfer or sharing of electrons
- how ions are formed when atoms gain or lose electrons and how giant ionic lattices are held together by the attraction between oppositely charged ions
- how covalent bonds are formed when atoms share electrons
- that substances with covalent bonds may form simple molecular structures or giant structures
- ways in which the physical properties of some substances with giant structures differ from those with simple molecular structures. (DfEE/QCA, 1999, p. 51)

145 of the students in the original sample had studied to this level as part of their preparation for school leaving examinations (the General Certificate of Secondary Education, GCSE). The other 209 students in the original sample were studying post-compulsory courses having completed their secondary education. These students would generally be 16-18 years of age, and they were studying chemistry at A-level. This is the standard university entrance qualification in England, and students are usually only accepted onto these courses on the basis of strong performance in the GCSE examinations. These students therefore are more selective, both in the sense of having chosen chemistry as one of their (usually 3-4) study subjects, and in the sense of having met selection criteria for advanced study. 81 of these students in the original sample had not yet studied the bonding topic further since completing their school courses.

Students at A-level typically (as there is a choice of examination boards which may set the precise specifications of their courses) studied more advanced models of bonding, for example in terms of combinations of atomic orbitals. They would study such topics as the Born-Haber cycle and consider factors influencing lattice energies. They would also learn about electronegativity, and how this determined the characteristics (e.g. extent of ionic bonding) of bonding in compounds, and how the charges and sizes of ions could be considered to polarize ions in lattices. 128 of the students in the original English sample were A-level students, having studied the topic of bonding at this higher level. It is this sub-sample which is considered in this paper, as offering the most comparable group to the students setting out on University level courses in the Greek and Turkish samples.

The Greek context and sample

In Greece, there is a nine-year compulsory education, six years of primary education (grades 1-6), and three years of lower secondary school (grades 7-9). Science is taught systematically as an integrated subject in grades 5 and 6, and as separate subjects (biology, physics, and chemistry) in grades 7-9. Upper secondary school (lykeion) has three grades (10-12), and here again science is taught as separate subjects. In lykeion there is a distinction between subjects for general education, and advanced courses for specialized streams of studies. For the students of our sample, physics was taught in all three grades (for three, two and one periods per week respectively), chemistry in grades 10 and 11 (each for two periods), and biology in grades 11 and 12 (each for one period). Note that starting in the school year 2011-12 at grade 10, a restructuring of the curriculum of the Greek lykeion is in progress, but the teaching of the bonding concepts at grade 10 has not ben altered so far,

All students follow the same courses up to the end of grade 10. Starting at gGrade 11, students had to follow one of three streams: The 'Positive' Stream, the 'Theoretical' Stream, and the 'Technological' Stream. In grade 12, each stream has four specialised courses, which were tested nationally and used for entrance to tertiary education. The Positive Stream was for students who want to study science, engineering, agricultural studies, and related applied subjects, or medicine and related subjects. The Theoretical Stream was for students who wanted to study literature, law, humanities, and so on. Finally, the Technological Stream leaded to the same studies as the Positive Stream, except for medical subjects. Chemistry was taught as a specialized course only in the Positive Stream. A national curriculum with a standard book published by The Greek Pedagogic Institute is followed strictly.

To enter tertiary education, Greek students take national entrance examinations that are organised and carried out by the Ministry of Education, Lifelong Learning and Religious Affairs.

Chemistry was examined as a tertiary education entrance subject only for the students of the Positive Stream.

The concept of chemical bonding is taught systematically in lykeion. Ionic and covalent bonding is first introduced in grade 10. Chemical bonding is treated in terms of the transfer (ionic bonding) or sharing of electrons (covalent bonding) respectively. Metallic bonding is then introduced. Intermolecular forces (Van der Waals forces, and hydrogen bonding) are treated separately.

The Greek sample of the present study derived from various first-year university departments as follows: (1) Chemistry (moderate achievement) (n = 66); and (2) Biological Applications and Technologies (moderate to higher achievement) (n = 102). ("Achievement" refers to achievement in the Greek University Entrance Examination.) These students took the ionic-bonding test at the beginning of the academic year (age 18-19), before the university chemistry course had dealt with bonding concepts. Therefore, the knowledge on which the students based their answers was that received in their upper secondary chemistry courses.

The Turkish context and sample

In Turkey, elementary education has grades 1-5, ages 7-11, and upper elementary education has grades 6-8, ages 12-14, and science lessons start in grade 4. Secondary education comprised grades 9-11, ages 15-17, until the 2005/6 academic year; then from the academic year 2006/7 it comprises grades 9-12, ages 15-18. All Turkish students in our study attended secondary education for three years.

In grades from 4 to 8, science is taught as an integrated science course, including chemistry, biology and physics concepts and topics. In secondary education chemistry, biology, and physics are taught as separate subjects in all classes/grades. The formal chemistry courses, which go on for four years, start with secondary education, which is also called high school or Lycée.

Turkey uses a strict national curriculum for every course in elementary and secondary education. The bonding concept is first taught to students in science lessons in grade 8, with brief explanations of ionic and covalent bonding. Chemical bonding features regularly in the Turkish high school chemistry curriculum. By the end of secondary schooling, students were expected to have learnt, *inter alia*, the following ideas about chemical bonding, i.e.

- that new substances are formed when atoms combine
- that chemical bonding can be explained in terms of the transfer or sharing of electrons
- how ions are formed when atoms gain or lose electrons and how giant ionic lattices are held together by the attraction between oppositely charged ions
- how covalent bonds are formed when atoms share electrons
- that substances with covalent bonds may form simple molecular structures or giant structures
- the physical properties of ionic, metallic, covalent, and molecular solids
- the importance of intermolecular forces in forming substances.

Turkish samples derived from various first-year university departments (at the beginning of the academic year 2009, age 18-19), as follows: (1) Chemistry (CHE) (low achievement) (n = 70); (2) Chemistry Education (intermediate achievement) (n=20); (3) Mathematics Education (very high achievement) (n = 49); (4) Elementary Mathematics Education (high achievement) (n = 112); and (5) Computer-Education and Instructional Technology (intermediate achievement) (n = 37). ("Achievement" refers to achievement in the Turkish University Entrance Examination.)

Methodology

The original English language version of the refined diagnostic instrument is presented in Appendix 1. The 20-item instrument was administered to students from Greece and Turkey. The instrument was first translated into the languages of instruction in those contexts. The Greek translation was carried out by two experts, with good knowledge of English (one of the authors, GT, plus a graduate student). Translation into Greek presented no problems – for clarity, only in two cases there were changes in the wording of the original items: the verb "bonded to …" was rendered into Greek as "connected with bond with …"; in addition, the expression "bonded to any neighbouring ions" was rendered into Greek as "connected with bond to any neighbouring ion provided that it is sufficiently close to it". The Turkish version of the instrument was translated into Turkish by author CN, and was then checked by an English lecturer. To establish the content validity of the instrument for Turkish sample, the secondary school chemistry curriculum was examined by author CN.

The instrument was completed by students individually, using a pencil or pen to indicate whether they thought a statement to be 'true' or 'false'. One version of the published instrument includes an alternative response option of 'I don't know', intended to reduce the extent of guessing. The students show their answer by ringing one of the response categories on a response sheet. In practice a few students will (deliberately or through carelessness) leave an item, or accidently indicate two responses for the same item. Such missing and ambiguous responses are rare (see tables A2-A4 in appendix 2). In the English and Turkish samples, modest proportions of students opted to use the 'do not know' response category (see appendices 1 and 3). In the application of the test in Greece, the version of the instrument was used in which the option "I don't know" was not offered to the students. In this particular application, only one student answered in one question with "I don't know". In the results presented below we present the percentages selecting particular statements as true, and note that the use of the 'forced choice' form of the instrument in Greece somewhat reduces the comparability across contexts.

Facility of the instrument items

Each of the items in the instrument can be considered to be a true or false statement in terms of the canonical knowledge presented in the curriculum and taught in chemistry classes (see Appendix 1). It is therefore possible to consider the overall facility of the instrument in terms of the percentage of correct responses on each item, and across the instrument. These figures have been calculated for the original English sample (Taber, 1997) for their responses on the 20 items used in the Greek and Turkish studies, to allow a comparison to be made.

Comparing across the three countries

The authors working in Greece and Turkey administered the instrument to samples of first year undergraduate students prior to university instructions about the topic, so the most comparable English sample is those who had studied this topic at University entrance level. All cross-national comparisons below therefore use this group as the English sample.

Findings

Table 1 shows the percentage of students giving correct responses, as a percentage of total classifiable responses. This table summarises more detailed information provided in Appendices 2-4, where the full responses patterns in each sample are given.

Item	**England** (n = 128)	**Greece** (n = 168)	**Turkey** (n = 288)
1	90	55	62
2	75	29	33
3	33	24	20
4	29	43	14
5	51	42	33
6	40	32	19
7	89	49	78
8	63	44	57
9	84	59	63
10	38	36	32
11	57	32	37
12	34	27	25
13	62	71	60
14	77	36	54
15	83	63	74
16	41	41	31
17	78	38	56
18	37	22	16
19	62	45	67
20	37	70	23
Overall	57.9	43.0	42.7

Table 1: The percentage of correct responses for each item in the three samples

It is clear from Table 1, that there is a different pattern of performance across items in the test instrument across the three samples, which is shown graphically in Figure 5.

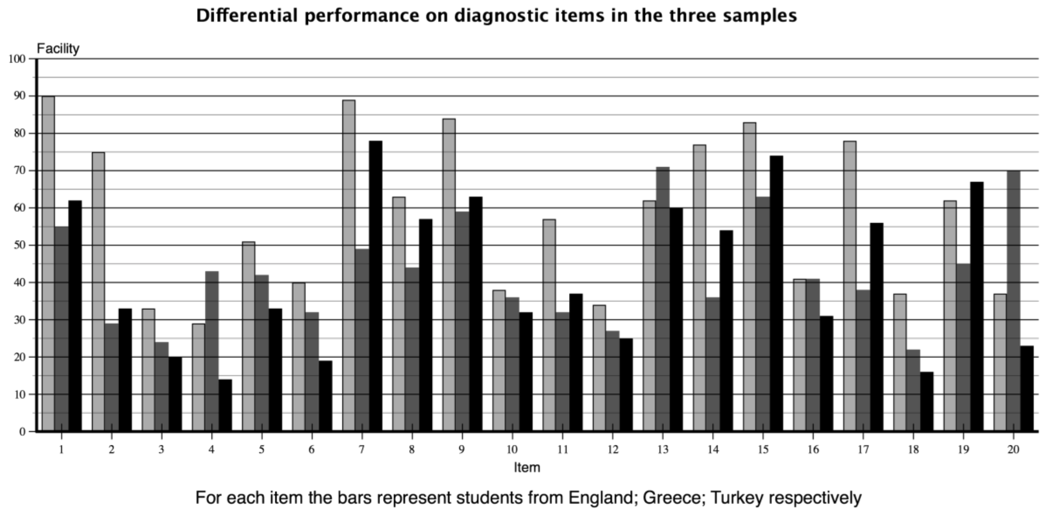

Figure 5: Differential performance on diagnostic items in the three samples

In order to consider the pattern of results in more detail, the findings are discussed in terms of clusters of items relating most strongly to the curricular electrostatic framework, and to the main aspects of the alternative molecular framework.

Recognition of electrostatic principles – the curriculum science framework

Seven of the twenty items in the diagnostic instrument presented statements that reflected the canonical knowledge students are expected to learn. This is that ionic bonding is primarily the outcome of electrical interactions between positive and negative ions, which about attracted together into a tightly bound lattice (i.e., until the ions are close enough for repulsions between electrons in different ions to balance the attractions between the charges). The bonding is the electrical interaction. Whilst this is not the most sophisticated model chemists could present, it represents a suitable basis for college and undergraduate students to appreciate the properties of ionic solids (Gillespie, 1997).

Table 2 presents the level at which students in the three educational contexts thought the statements based upon the curriculum model were true.

Item	Statement	England / %	Greece / %	Turkey / %
1	A positive ion will be attracted to any negative ion.	90	55	62
9	A negative ion will be attracted to any positive ion.	84	59	63
7	An ionic bond is the attraction between a positive ion and a negative ion.	89	49	78
15	The reason a bond is formed between chloride ions and sodium ions is because they have opposite charges.	83	63	74
8	A positive ion will be bonded to any neighbouring negative ions.	63	44	57
19	A negative ion will be bonded to any neighbouring positive ions.	62	45	67
20	There are no molecules shown in the diagram.	37	70	23

Table 2: Student rating of statements reflecting the canonical electrostatic model of ionic bonding

The seven statements relate to three particular foci: attractions between ions, bonding between ions, and the absence of molecules. From the perspective of the electrostatic framework (curricular knowledge) the bonding is electrostatic. However, from the perspective of the alternative molecular framework, a bond is seen as something more than just an attraction due to opposite charges, and so 'bonding' and 'attraction' may seem to refer to quite different things. Students have been found to make quite idiosyncratic judgements about whether particular chemical structures involve bonds or attractions: for example recognising the presence of bonding where they do not recognise chemical bonds, or recognising the presence of forces between species, but not attractions (Taber, 2002b, pp. 126-127).

Generally, the English students agreed with this set of statements, apart from most disagreeing with the absence of molecule – suggesting that there was a strong commitment to the idea of molecules as the basic unit of a chemical structure. Similarly, a majority of the Turkish students tended to agree with six of these statements, but over three quarters reject the statement denying the presence of molecules. By comparison, the Greek sample performed best on this particular item, although, only a minority of the Greek students accepted that an ion would be bonded to *any* neighbouring counter ion.

The alternative conceptual framework

The majority of the statements in the instrument (13/20, see appendix 1) were written to represent aspects of the alternative conceptual framework, the molecular framework for understanding ionic bonding. These items are considered here grouped according to the main features of the framework as shown in figure 1.

Statements reflecting the 'history conjecture' alternative conception

The 'history conjecture' refers to identifying ionic bonding with a hypothetical electron transfer event imagined as forming the bonded ions, and considered as a prerequisite for the presence of a bond. That is, the bond is seen as contingent upon the ions having the shared history of having donated and accepted electrons, rather than simply being due to electrical interactions. In this context it may well be relevant that students in Taber's original interview study sometimes considered an electron to be in a sense owned by a particular atom (where it was assumed to have originated), so that it was thought that when covalent bonds were broken the bonding electrons necessarily returned to their original atoms (Taber, 1998). This kind of thinking would almost consider a transferred electron as only 'loaned' from the cation to the anion (and may explain why some students apparently consider that during precipitation reactions the original loan first must be repaid, before a new transaction is undertaken to form the ions that will be bonded in the precipitate).

Item	Statement	England / %	Greece / %	Turkey / %
2	A sodium ion is only bonded to the chloride ion it donated its electron to.	20	71	67
11	A chloride ion is only bonded to the sodium ion it accepted an electron from.	37	68	63
10	It is not possible to point to where the ionic bonds are, unless you know which chloride ions accepted electrons from which sodium ions.	52	64	68
4	The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.	70	57	86
18	An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.	61	78	84

Table 3: Student agreement with statements reflecting the history conjecture alternative conception

Five statements in the instrument were associated with the 'history conjecture' alternative conception. Table 3 presents these five statements, and the level of support for them in the three national contexts. The numbers given show the percentage of those offering unambiguous responses that the statements were true.

Writing clear and unambiguous items, that are also succinct and readily comprehended, can be challenging. The first four items listed in Table 3 are open to the criticism that in the molecular framework it is discrete *atoms* that interact to form *ions*, and so strictly these items are not correctly worded. For example, item 2 might be more accurately (if less concisely) be worded as 'a sodium ion is only bonded to the chloride ion *formed from the chlorine atom that* it donated its electron to'; and item 4 might more strictly be worded as 'the reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between *sodium and chlorine atoms from which they were formed*'. We do not suspect that this issue will have been a factor in many students' ratings of the statements, as, if anything, a pedantic reading of the items would have led to Table 3 under-representing the degree to which respondents thought the ionic bond depended upon a prior electron transfer event.

Only a minority of the English sample agreed with statements 2 and 11 (which suggested that ionic bonds were limited to where electron transfer had taken place), whereas the majority of respondents in both the Greek and Turkish samples did agree with these statements. Items 10, 4, and 18 were selected by a majority of students in each of the three samples. Whilst electron sharing is arguably a useful metaphor for covalent bonding, as suggested above the association between ionic bonding and electron transfer is highly misleading. It is possible to argue that, hypothetically, if an electron was transferred between adjacent, discrete sodium and chlorine atoms, the resulting ions would attract, from which perspective items 4 and 18 *could be construed* as correct. However, discrete sodium and chlorine atoms are not commonly found in feasible chemical contexts, so this is unlikely. Further, as the ionisation energy of sodium exceeds the electron affinity of chlorine, such a transfer would both require specific energy input, and lead to an unstable system that would be expected to decay back to the separate atoms.

Moreover, in the laboratory contexts with which students are likely to be most familiar (forming NaCl by neutralisation followed by evaporation; formation of ionic precipitates by double decomposition) ionic bonding is formed between ions already present without any electron transfer events being necessary.

Statements reflecting the 'valency conjecture' alternative conception

If a student considers that an ionic bond only occurs where atoms have transferred electrons to form bonds, then this would imply that the number of counter ions that an ion could bond with is not determined by its coordination number within a lattice, but rather is limited by the number of electrons transferred. In a simple case, such as NaCl, where the ions have a charge of magnitude 1 (i.e. considered to form by the donation or acceptance of a single electron), then each ion is judged to only form a single ionic bond.

Four statements in the instrument were associated with the 'valency conjecture' alternative conception. Table 4 presents these four statements, and the level of support for them in the three National contexts.

Item	Statement	England / %	Greece / %	Turkey / %
3	A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.	64	76	80
12	A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.	63	73	75
14	A negative ion can only be attracted to one positive ion.	21	64	46
17	A positive ion can only be attracted to one negative ion.	20	62	44

Table 4: Students agreement with statements reflecting the valency conjecture alternative conception

The items in Table 4 consist of a pair of statements worded in terms of bond formation (items 3 and 12) and a pair of statements worded in terms of attraction between ions (items 14 and 17). This is reflected in the broadly similar responses within the pairs for each sample. In the English sample there was a strong distinction between the pairs, in that only about a firth of the sample thought an ion could only be *attracted* to one other counter ion, whereas over three-fifths thought that the ion could only be *bonded* to one counter ion. There was a similar distinction in the Turkish sample, although with higher support for both sets of statements. The pattern for the Greek sample was different, with a majority of respondents thinking the number of attractions, as well as bonds, would be limited as suggested by the valency conjecture.

Statements reflecting the 'just forces conjecture' alternative conception

If the number of ionic bonds linking each ion to counter ions is thought to be limited by the ionic charge (the valency conjecture, see above), then the interactions (if any) between an ion and the other neighbouring counter ions must be something *other than* ionic bonding. It was suggested by some students in Taber's original interview study that these interactions were not bonds, but just forces. However, there are other possibilities, such as there being one ionic bond, and five physical bonds, as suggested by the student reported by Butts and Smith (1987).

Three statements in the instrument were associated with the 'just forces conjecture' alternative conception. Table 5 presents these three statements, and the level of support for them in the three national contexts.

Item	Statement	England / %	Greece / %	Turkey / %
5	In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.	41	58	67
16	In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.	52	59	69
13	There is a bond between the ions in each molecule, but no bonds between the molecules.	26	29	40

Table 5: Students agreeing with statements reflecting the just forces conjecture alternative conception

Items 5 and 16 made parallel claims about anion and cations, which was reflected in the similarity of responses in the Greek and Turkish samples (although less so in the English sample), where clear majorities of respondents agreed with the statements making distinctions between bonds and 'just' forces.

Agreement with item 13 would require thinking of NaCl in terms of discrete molecules that had no intermolecular bonds between them (in the solid state). Given this, the more modest, but still substantial, proportions of students agreeing with this item is noteworthy. The level of agreement with this item among the Greek sample is consistent with the strong agreement with item 20 (see Table 2).

Statements reflecting the presence of molecules alternative conception

Where students think that ionic bonding is contingent upon electron transfer, and so that each ion can only be ionically bonded with one counter-ion, this implies that pairs of ions considered to be ionically bonded to each other (but not to other neighbouring ions) are perceived as being to some extent discrete units in the lattice. This was explicitly represented in item 6 in the instrument. This is shown in Table 6 with item 13 (repeated from Table 5) and item 20 (repeated from Table 2), for ease of comparison.

Item	Statement judged true	England / %	Greece / %	Turkey / %
6	In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion	56	68	81
13	There is a bond between the ions in each molecule, but no bonds between the molecules	26	29	40
20	There are no molecules shown in the diagram.	37	70	23

Table 6: Students agreeing with statements referring to molecules in sodium chloride. (Note: item 20 would be considered false from the perspective of the alternative framework)

Items 6 and 20 are contradictory, and this is reflected in the relative support for these two statements in the English and Turkish samples. Interestingly, clear majorities of the Greek students agreed with both these items. This is even more noteworthy, when it is recognised that for many Greek students referring to ions being 'contained' in a molecule would seem very awkward. There is a good case for arguing that a term such as 'comprises' or 'consists' would be more appropriate here, although as always there is a need to balance precision and accessibility of the language used in statements presented to learners.

Discussion

The data from the English study (Taber, 1997) had demonstrated that statements based upon the alternative ideas making up the molecular framework for understanding ionic bonding (see figure 4) identified from student interviews were commonly judged to be true by English students studying at upper secondary level, including those having studied the topic at University entrance level. Statements relating to the 'history', 'valency' and 'just forces' conjectures, as well as about the presence of molecules in NaCl, all received strong – and often majority - support. However, it was also the case that student support for the different statements based on the alternative conceptual framework varied considerably, and that students also commonly thought statements based on the canonical electrostatic model were also true. Indeed it was pointed out that the high level of support for many statements was only possible because some students were judging as true statements from both the curriculum and alternative frameworks, which from a scientific perspective would seem to contradict each other. It was suggested that many students held multiple frameworks of ionic bonding, having available (and finding plausible) aspects of both the alternative and scientific models.

Alternative conceptions of the ionic bond found among Greek and Turkish students

The present study reports new data from two other European contexts - Greece and Turkey – where students responded to translations of the 20-item version of the instrument published by the UK's Royal Society of Chemistry (Taber, 2002a). Our first research question was:

- Does the Truth about Ionic Bonding Diagnostic Instrument suggest that students in Greece and Turkey acquire the alternative conceptions about ionic bonding found in the earlier interview study in England?

Although the survey instrument was informed by the findings of an interview study that elicited student thinking about ionic bonding, we are aware that there are inherent limitations in interpreting responses when students are given closed option choices (such as whether a presented statement is true or false). Language is idiosyncratic to some extent, so we cannot be confident that different people have quite the same meanings and associations for terms – so for example individuals do not all use even such basic terms as force, attraction, bond and bonding in identical ways (Taber, 2002b). When faced with phrasing that is not their own, respondents have to make holistic judgements about whether to accept or reject a statement when, for example, 'that's kind of what I think, but not quite'. Asking students to consider presented statements is likely to overestimate support for particular conceptions compared with open-ended elicitation of ideas;, and given that there is always a balance to be drawn between the conciseness and specificity of an item, presented statements have potential to be considered 'leading'.

Given these various concerns, we do not consider that our results should be taken as indicating the levels at which these alternative conceptions were strongly committed to by respondents, but rather the levels are which students found presented statements to be consistent with their own ways of thinking. However, even this weaker interpretation suggests that alternative conceptions about ionic bonding are at least found plausible and reasonable by substantial proportions of students across different educational contexts.

The present study suggests that the topic of ionic bonding is conceptually challenging for Greek and Turkish students, as Butts and Smith (1987) had found in their work with Australian students. Alternative conceptions reported in previous studies were reflected in the present study. Students from Greece and Turkey commonly agreed with statements suggesting NaCl contained molecules (Butts & Smith, 1987; Levy Nahum et al., 2004; Taber, 1994, 1997; Ünal et al., 2010); that electron transfer was necessary for ionic bonding (Coll & Taylor, 2002; Coll & Treagust, 2003; Taber, 1994, 1997; Ünal et al., 2010); that that electrovalency limited the number of ionic bonds formed (Taber, 1994, 1997); that the ionic lattice comprised of ions that were ionically bonded to some counter-ions, and attracted by other by 'just forces' (Taber, 1994, 1997).

Patterns across different educational contexts

We noted above that the development of alternative conceptions are influenced by a range of factors. Intuitive responses to everyday phenomena (diSessa, 1993; Taber & García Franco, 2010) are related to features of human perception and cognition, and are likely to be common across learning contexts. Folk-science notions that have common currency in the 'life-world' of everyday life (Claxton, 1993; Solomon, 1993), and the interpretation of linguistic cues (Schmidt, 1991) are more likely to vary between different educational contexts as they depend upon cultural and linguistic features. Arguably, aspects of the specific teaching models and approaches adopted (Taber, 2003) may have an intermediate level of commonality, as although there will be local differences in teaching models and curriculum, the nature of target knowledge set out in chemical curriculum is moderation by the discourse of the international scientific community.

Our second research question was

- Are there any patterns in the national profiles of responses to the Truth about Ionic Bonding Diagnostic Instrument that could suggest that differences between the three different cultural and educational contexts influence the way students come to understand the ionic bond concept?

In looking to discuss comparisons across these different contexts, we highlight two caveats relating to our data sets. Firstly the English data was collected some time ago, and among students studying at University entrance level – not all of whom would have sought, or been awarded, places on science related university courses. By comparison, the Greek and Turkish samples represent recent students successful in obtaining University places on chemistry-related degree courses. This would be a serious impediment if we were seeking to make specific comparisons of student proficiency in the topic across these three contexts. However, our aims here are more modest, and we acknowledge that none of our samples can be considered to be representative of national contexts in a statistical sense. Accordingly we make no attempt to demonstrate statistically significant differences between the three samples, which would be quite inappropriate. However, we do note that our findings suggest that such comparisons based upon contemporaneous and representative national samples could be very informative, should resources become available for such work.

What our present study shows clearly is that when Greek and Turkish students setting out on chemistry related university courses were asked to consider statements which were inconsistent with the scientific understanding of the nature of bonding in NaCl, but which reflected the alternative molecular framework, they often judged these statements as true. That is, the alternative conceptions which were elicited from English students in interviews, and then found to be common among English students responding to the original version of the instrument, also seem to be common in these two other educational contexts, with their own curriculum structures and traditions, and where the topic is taught in their own national languages. Indeed, inspection of Table 1 suggests (subject to our caveats about drawing direct comparisons between samples) that, if anything, the alternative conceptual framework reflected student thinking among the Greek and Turkish samples to *a greater extent* than in the English sample.

It is intriguing that the overall 'performance' (in terms of how statements would be judged from a canonical perspective) on the instrument was very similar for the Greek and Turkish samples (c. 43%), although this 'headline' figure disguises a complex pattern of differences in responses on particular items (Figure 5). Although we are not claiming that these samples are statistically representative of national populations, there are some large differences in response rates between the samples worthy of comment.

It is noticeable that students in both the Greek and Turkish samples were much more likely to judge that an ion in NaCl could only be bonded (on items 2, 11, see Table 3) or even attracted (items 1, 9, see Table 2; and items 14, 17, see Table 4) to one other ion, than the respondents in the original English sample. However, this difference was less pronounced on two other related items (8, 19, see Table 2), suggesting (again`, cf. Taber, 1997) that the precise wording of items (or possibly a cuing effect, due to the sequencing of questions) may be significant in how students respond to statements such as these. This is important in reminding us that although simple pencil-and-paper instruments allow the collection of data from large samples, they only provide a snap-shot of thinking: progress in understanding exactly how students generally understand complex scientific concepts requires a research programme offering iteration between in-depth exploration of individuals (for example, using interviews) and testing out the extent of ideas uncovered in surveys (Taber, 2009).

The students in the Turkish sample recognised an ionic bond as an electrostatic attraction to a much greater extent than the sample of their Greek neighbours (item 7, Table 2), as well as being less likely to think an ion could only be attracted to one counter ion (items 14, 17, see Table 4). We wonder if there was a linguistic effect in operation here, as the Greek phrasing of (when retranslated to English) 'connected with bond' may reinforce the notion of the bond as material link rather than a force.

Also, although a modest majority of the Greek respondents considered electron transfer *the reason* for bond formation in NaCl, this alternative conception was much less popular among these respondents than among the Turkish sample (item 4, see Table 3): conceivably, this again could be related to Greek phrasing implying bonding being a material connection.

Conversely, students in the Greek sample were much more likely to recognise that there were no molecules shown in the diagram (Figure 2) of NaCl (item 20, see Table 2), which we consider reflects the Greek curriculum and textbooks emphasising that the notion of molecule in ionic compounds makes no sense.

It seems then that some of the differences we find between national samples seem much too large to be due to idiosyncrasies of the particular samples. This is especially so when considering the Greek and Turkish samples, which were made up of similar groups of undergraduates, and who demonstrated very similar overall performance on the instrument. So these differences seem likely to be cultural – related to features of the teaching and learning context: such variables as aspects of the way chemistry is presented in the Greek and Turkish languages; the organisation and sequencing of the curriculum; the approaches taken in text books; the common teaching models and analogies offered by teachers.

Implications for instruction

The patterns found in student responses across the three national contexts are intriguing. It is not entirely clear from the present study why particular statements representing specific alternative conceptions receive different support for the different samples of students. The misleading and scientifically inaccurate idea that ionic bonding can be explained by the transfer of electrons has become part of target knowledge in all three contexts, and which no doubt contributes to students' demonstrating alternative conceptions. However, in the English context this seems to have been moderated to some extent by target knowledge presented at secondary level also including how ionic lattices are held together by the attraction between oppositely charged ions (DfEE/QCA, 1999, p. 51). That is, the curriculum refers to the electrical interaction between charges, as well as referring to electron transfer as 'explaining bonding'.

We would recommend that the misleading notion that ionic bonding can be explained by electron transfer should be eliminated from curricula, and avoided by teachers, who should instead focus on discussing how an ionic lattice forms due to the mutual attraction between oppositely charged ions. It may also be helpful to focus on the notion of ionic *bonding* (understood as a lattice phenomenon), rather than talking of the ionic *bond* (perhaps implying discrete interactions between ions).

We would suggest that the idea of ions, and their differences from neutral atoms and molecules, should be introduced prior to, but not as part of, teaching about bonding. Then ionic bonding can be introduced without a need to focus on ion formation. There is little chemical sense is starting discussion of ionic bonding by considering discrete neutral atoms, and a better starting point would be with the demonstration of the formation of an ionic solid by neutralisation and evaporation (e.g. NaCl), and/or by precipitation (e.g., AgCl). Then the focus is on why the ions, already present in the reactant solutions, form into an ionic lattice due to ionic bonding. The teaching should focus on the electrical interactions between ions, and how these lead to regular packing with cations surrounded by anions and vice versa.

Only once this basic process has been taught, and is appreciated by students, using an example with electrovalencies of +1 and -1 (e.g. Na^+, Cl^-), should the complication of different possible ionic charges can be discussed. However, here the foci should be on (a) how a larger charge can lead to a stronger attraction; (b) how the lattice still needs to be neutral in cases such as $CaCl_2$, Na_2SO_4, etc. (determining stoichiometry). These contexts should be used to reinforce the idea that each ion is equally attracted to as many counter ions as are able to cluster around it in the lattice.

We noted above that Greek students were much more likely to deny the presence of molecules in an ionic lattice than Turkish or English students, and suggested this might reflect an emphasis in the Greek context that makes it explicit that the notion of ionic molecules is non-sensible. This suggests that there may be value in this explicit treatment of the alterntive conception being adopted in other contexts. For example, once students have been introduced to solids at room temperature with ionic and simple molecular structures, it might be valuable to make an explicit comparison between the component units in the solid and liquid phases, and in solution, and how this difference explains differences in properties (see Table 7).

Structure	Simple molecular	Ionic
Solid	Discrete molecules, weakly attracted to other molecules: often soft, often modest melting temperatures	Network of ions strongly attracted to oppositely charged ions: often hard, often high melting temperatures
Liquid	Discrete neutral molecules: non-conducting	Discrete ions: will conduct electricity
Solution	Discrete molecules mix with molecules of non-polar solvent: non-conducting	Discrete ions become solvated by molecules of polar solvent: solution will conduct electricity

Table 7: The significance of the presence of ions, but absence of molecules, in ionic materials should be emphasised in instruction

The work of Mendonça and Justi (2010) illustrates how a teaching scheme that incorporates asking students to work in teams to build models which can explain such patterns in properties can be successful in helping learners develop their thinking about ionic bonding in line with canonical knowledge.

The value of comparing across national contexts

Understanding the similarities and differences in the ways students tend to think in different educational contexts presents challenges to research. To be done well it requires cross-national research teams resourced to undertake national surveys of both representative samples of students, and of the learning contexts themselves – something well beyond the scope of the present study. However, where common alternative conceptual frameworks are reported in particular contexts, it is valuable to explore the extent to which they are found in other contexts, if only to inform teachers working in those contexts. Students in Greece and Turkey, like those in England, would seem to commonly think about bonding in ionic structures in terms of electron transfer leading to localised bonds between pairs of ions, rather than an interaction that occurs between any oppositely charged ions that are in close proximity. Greek and Turkish teachers, like English teachers, should be made aware of this.

Clearly this is not a simple matter of students either adopting the canonical electrostatic model, *or* holding the alternative conceptual framework: in all three samples discussed here, students make nuanced judgements about which particular statements (from both frameworks) may be correct, suggesting that often their thinking is a mixture of, perhaps in transition between, these two broad perspectives. The 'molecular' framework is a conceptual framework in the sense of Gilbert and Watts (1983): a model of commonalities found in student thinking, not an encapsulated cognitive element which is necessarily applied wholesale. So although Greek students tended not to think in terms of molecules, they still tended to agree with a range of statements that were consistent with treating NaCl structure as if its basic unit was a molecule-like NaCl ion pair.

The main messages from our present study then are two fold. Firstly, that particular alternative conceptions about ionic bonding in NaCl are influential in the thinking of students across several national contexts. This suggests that these alternative conceptions are not specific to a peculiarity of the way the topic is taught in a single educational context. At the very least, commonalities in the way this topic is taught in different languages, and following different curriculum programmes, encourage the same alternative ways of thinking. It is quite possible that general aspects of the way human cognition works may actually be responsible for biasing student thinking towards a distorted understanding of this concept area (cf. diSessa, 1993; Taber & García Franco, 2010).

Secondly, the large variations in the response rates on some items across the national contexts (and especially between Greece and Turkey where the samples were highly comparable, and performed at a very similar level overall) shows that despite the high incidence of these alternative ideas across the different systems, local or cultural factors do make a difference. Something similar has been found in terms of student thinking about ionisation energy, where support for alternative conceptions was found to be common across six national contexts, but with strong variations from one country to another (Tan et al., 2008). Studies such as that of Tan and colleagues, and the present study, indicate there is much potential to explore how local features of particular educational contexts interact with student learning to lead to higher or low levels of specific conceptions. In principle, such work has great potential to inform more effective pedagogy by identifying ways of presenting teaching which best supports the development of canonical scientific thinking rather than the acquisition of alternative conceptions.

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Appendix 1: The truth about ionic bonding diagnostic instrument

Item	Statement	T/F	Framework
1	A positive ion will be attracted to any negative ion.	true	electrostatic
2	A sodium ion is only bonded to the chloride ion it donated its electron to.	false	molecular (H)
3	A sodium atom can only form one ionic bond, because it only has one electron in its outer shell to donate.	false	molecular (V)
4	The reason a bond is formed between chloride ions and sodium ions is because an electron has been transferred between them.	false	molecular (H)
5	In the diagram a chloride ion is attracted to one sodium ion by a bond and is attracted to other sodium ions just by forces.	false	molecular (J)
6	In the diagram each molecule of sodium chloride contains one sodium ion and one chloride ion.	false	molecular (M)
7	An ionic bond is the attraction between a positive ion and a negative ion.	true	electrostatic
8	A positive ion will be bonded to any neighbouring negative ions.	true	electrostatic
9	A negative ion will be attracted to any positive ion.	true	electrostatic
10	It is not possible to point to where the ionic bonds are, unless you know which chloride ions accepted electrons from which sodium ions.	false	molecular (H)
11	A chloride ion is only bonded to the sodium ion it accepted an electron from.	false	molecular (H)
12	A chlorine atom can only form one ionic bond, because it can only accept one more electron into its outer shell.	false	molecular (V)
13	There is a bond between the ions in each molecule, but no bonds between the molecules.	false	molecular (M; J)
14	A negative ion can only be attracted to one positive ion.	false	molecular (V)
15	The reason a bond is formed between chloride ions and sodium ions is because they have opposite charges.	true	electrostatic
16	In the diagram a sodium ion is attracted to one chloride ion by a bond and is attracted to other chloride ions just by forces.	false	molecular (J)
17	A positive ion can only be attracted to one negative ion.	false	molecular (V)
18	An ionic bond is when one atom donates an electron to another atom, so that they both have full outer shells.	false	molecular (H)
19	A negative ion will be bonded to any neighbouring positive ions.	true	electrostatic
20	There are no molecules shown in the diagram.	true	electrostatic

Table A1: Items included in the diagnostic instrument

Notes: T/F refers to the 'truth' of the statements in terms of the canonical knowledge, i.e. the curriculum model of ionic bonding; framework shows whether statements reflect the curriculum (electrostatic) or alternative (molecular) conceptual framework. In the latter case statements are aligned with key conceptions in the framework labelled H, J, M, V for history, just forces, molecules and valency – see the main text for an explanation of the significance of these terms.

Appendix 2: Responses from the three samples

Response frequencies for English sample (advanced pre-university students)

item	T	F	T+F	D	•	A	N	*
1	115	10	125	3	128	0	0	128
2	24	96	120	7	127	0	1	128
3	76	42	118	8	126	0	2	128
4	88	37	125	3	128	0	0	128
5	45	65	110	17	127	1	0	128
6	65	51	116	10	126	0	2	128
7	114	10	124	3	127	0	1	128
8	81	34	115	12	127	0	1	128
9	107	12	119	5	124	1	3	128
10	53	49	102	25	127	1	0	128
11	42	73	115	13	128	0	0	128
12	73	43	116	10	126	0	2	128
13	28	79	107	18	125	0	3	128
14	26	99	125	0	125	0	3	128
15	106	17	123	3	126	0	2	128
16	57	53	110	17	127	0	1	128
17	25	100	125	3	128	0	0	128
18	74	47	121	7	128	0	0	128
19	79	38	117	11	128	0	0	128
20	47	62	109	19	128	0	0	128

Table A2: Response frequencies for English sample (advanced pre-university students)

T: number of 'true' responses

F: number of 'false' responses

T+F: Number of definitive ('true' or 'false') responses (used for determining percentages used in the paper)

D: number of 'I do not know' responses

• : Number of unambiguous ('true' or 'false' or 'I do not know') responses

A: Number of ambiguous responses (unclear answer, or two answers selected)

N: Number of non-responses (no response given for item)

* :Total number of students completing the instrument

Response frequencies for Greek sample (first year undergraduates)

Item	T	F	T+F	A / N	*
1	95	71	166	2	168
2	116	49	165	3	168
3	124	41	165	3	168
4	94	72	166	2	168
5	96	70	166	2	168
6	109	54	163	5	168
7	82	84	166	2	168
8	73	92	165	3	168
9	99	69	168	0	168
10	106	60	166	2	168
11	112	54	166	2	168
12	121	45	166	2	168
13	46	119	165	3	168
14	105	61	166	2	168
15	105	56	161	7	168
16	98	68	166	2	168
17	103	63	166	2	168
18	128	37	165	3	168
19	76	87	163	5	168
20	118	50	168	0	168

Table A3: Response frequencies for Greek sample (first year undergraduates)

T: number of 'true' responses

F: number of 'false' responses

T+F: Number of definitive ('true' or 'false') responses (used for determining percentages used in the paper)

A/N: Number of ambiguous responses (unclear answer, or two answers selected) and non-responses (no response given for item)

* : Total number of students completing the instrument

Response frequencies for Turkish sample (first year undergraduates)

Item	T	F	T+F	D	•	A	N	*
1	179	99	278	7	285	0	3	288
2	180	94	274	11	285	0	3	288
3	215	57	272	12	284	0	4	288
4	226	40	266	19	285	0	3	288
5	133	96	229	53	282	0	6	288
6	216	56	272	11	283	0	5	288
7	224	53	277	7	284	0	4	288
8	164	91	255	23	278	0	10	288
9	181	91	272	12	284	0	4	288
10	147	92	239	40	279	0	9	288
11	163	107	270	15	285	0	3	288
12	187	71	258	27	285	0	3	288
13	89	173	262	17	279	0	9	288
14	118	155	273	13	286	0	2	288
15	213	62	275	10	285	0	3	288
16	133	88	221	54	275	0	13	288
17	109	161	270	15	285	0	3	288
18	218	45	263	19	282	0	6	288
19	193	65	258	26	284	0	4	288
20	67	171	238	42	280	0	8	288

Table A4: Response frequencies for Turkish sample (first year undergraduates)

T: number of 'true' responses

F: number of 'false' responses

T+F: Number of definitive ('true' or 'false') responses (used for determining percentages used in the paper)

D: number of 'I do not know' responses

• : Number of unambiguous ('true' or 'false' or 'I do not know') responses

A: Number of ambiguous responses (unclear answer, or two answers selected)

N: Number of non-responses (no response given for item)

* : Total number of students completing the instrument

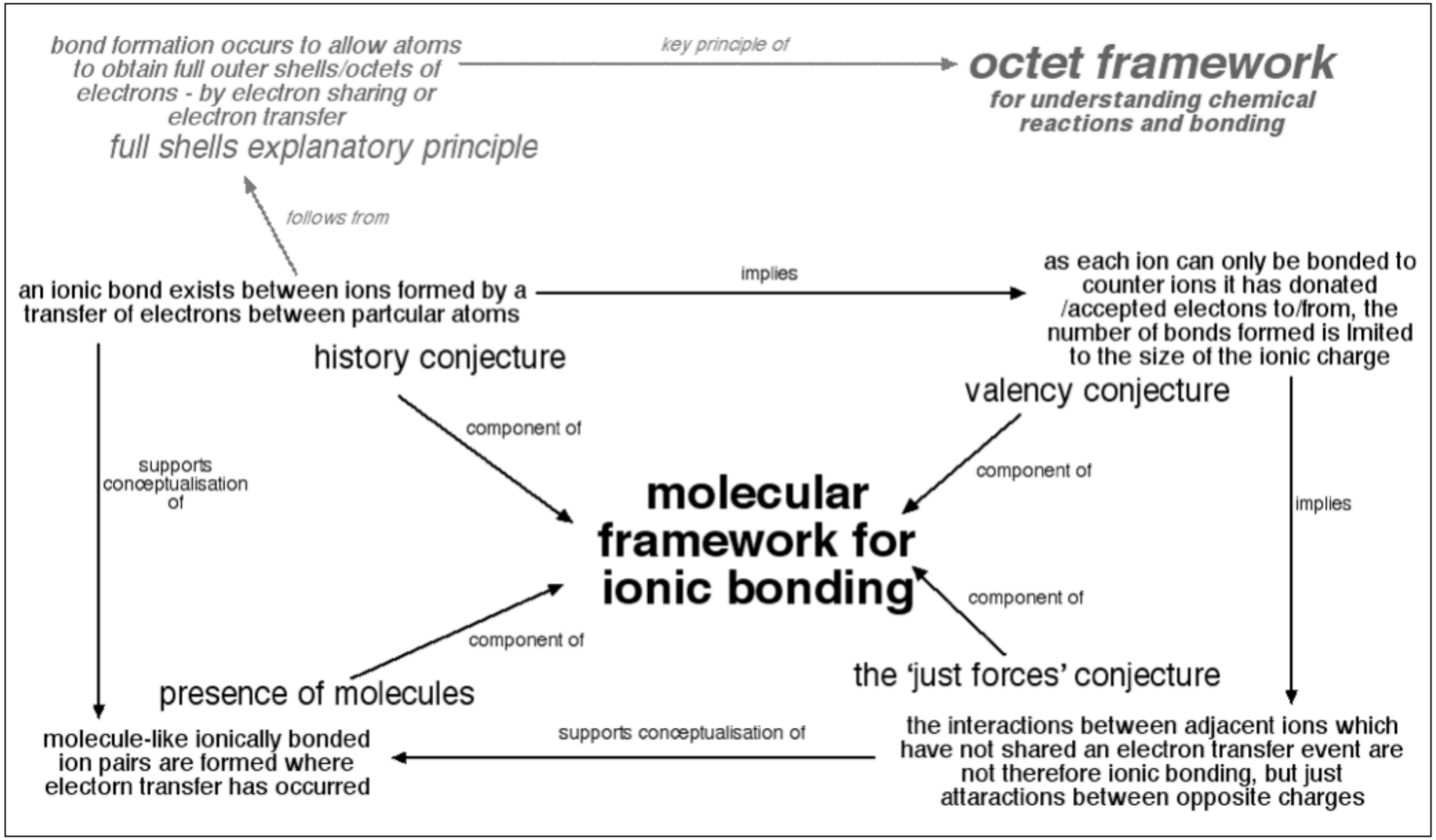

Figure 4: An alternative conceptual framework for ionic bonding representing thinking of English college students