DO VISUAL MODELS SUPPORT DEVELOPMENT OF SCIENTIFIC EXPLANATIONS OF IONISATION ENERGY VALUES?

Ruth Wheeldon
Institute of Education, University of London, UK

Abstract: Chemistry pupils and their teachers often use non scientific causal arguments in ionisation energy explanations. This research examines how activities which model the electrostatic character of electron/electron and electron/nucleus interactions can support the development of scientific explanations. 38 chemistry pre-service teachers (PSTs)' responses to true/false statements were analysed before and after the interventions in order to determine the change in explanatory ideas used. Six of these PSTs were also interviewed to similarly identify changes in their explanations. Responses were analysed using confidence levels to identify guessing and subsequently changes categorised the interventions as having one of four effects: A 'positive' one when responses indicated causal arguments used instead of earlier guessing or alternative ones; A 'no effect on a scientific concept' change when use of scientific causal arguments continued after interventions; A 'No effect on guessing or alterative ideas' category when PSTs continued to guess or use non-causal ideas in their responses. Finally a 'negative' change in responses was identified when scientific argument responses changed to become guesses or indicate alternative ideas were now used. 49 % of response changes to all statements were positive. 20% indicated an unchanging scientific concept was used to respond. However 12% of response changes were negative. Five of six interviewee explanations indicated developing use or retention of scientific arguments compared with all six showing improved or retained use of scientific arguments via changes in the true/false statement responses. These findings indicate that the development of causal arguments to explain ionisation energies is supported by activities that model coulombs law with respect to interactions between electrons and electrons and the nucleus in the atom. As these interactions are also responsible for chemical behaviours, development of these scientific principles supports a deeper understanding of chemistry more generally.

Keywords: pre-service teachers, Chemistry Conceptual Understanding, Modelling-based learning

INTRODUCTION

Research has shown that many students and their teachers (Tan, Taber, Liu, Coll, Lorenzo, Li, Goh, & Chia, 2008; Tan & Taber, 2009) explain variations in ionisation energy values in ways that are not consistent with scientific causal explanations. Some of the arguments that are used reveal alternative conceptions about the electrostatic properties of the electrons and nucleus of an atom. This research aims to evaluate the effectiveness of intervention activities developed to allow Pre-service teachers (PSTs) to form causal electrostatic arguments for subsequent ionisation energy values. The activities involve modelling the simultaneous effects of attraction and repulsion to account for ideas like Shielding by demonstrating its electrostatic character followed by using a bonfire analogy to visualise and describe these

electrostatic interactions and examining how the analogy's features provide useful explanatory resources.

RATIONALE

This paper aims to consider the efficacy of intervention activities via analysis of changes in response to true/false statements given before and after intervention. The activities aim to provide explanatory resources (via visual models) which support causal arguments, accounting for the differences in ionisation energy values.

METHODS

Questionnaire

An electronic questionnaire using statements based on Taber's (2002) ionisation energy true/ false diagnostic probe was used to determine electrostatic ideas. The statements all refer to a sodium atom and a diagram of a Rutherford/Bohr type representation was provided on each question slide as shown in figure 1. After the 'true' or 'false' response was given a further question prompted an indication of the answer confidence using a likert scale (Fig. 1). Table 1 shows only the statements used to probe electrostatic understanding and how they might reveal alternative ideas.

Fig 1: electronic voting screen showing confidence options

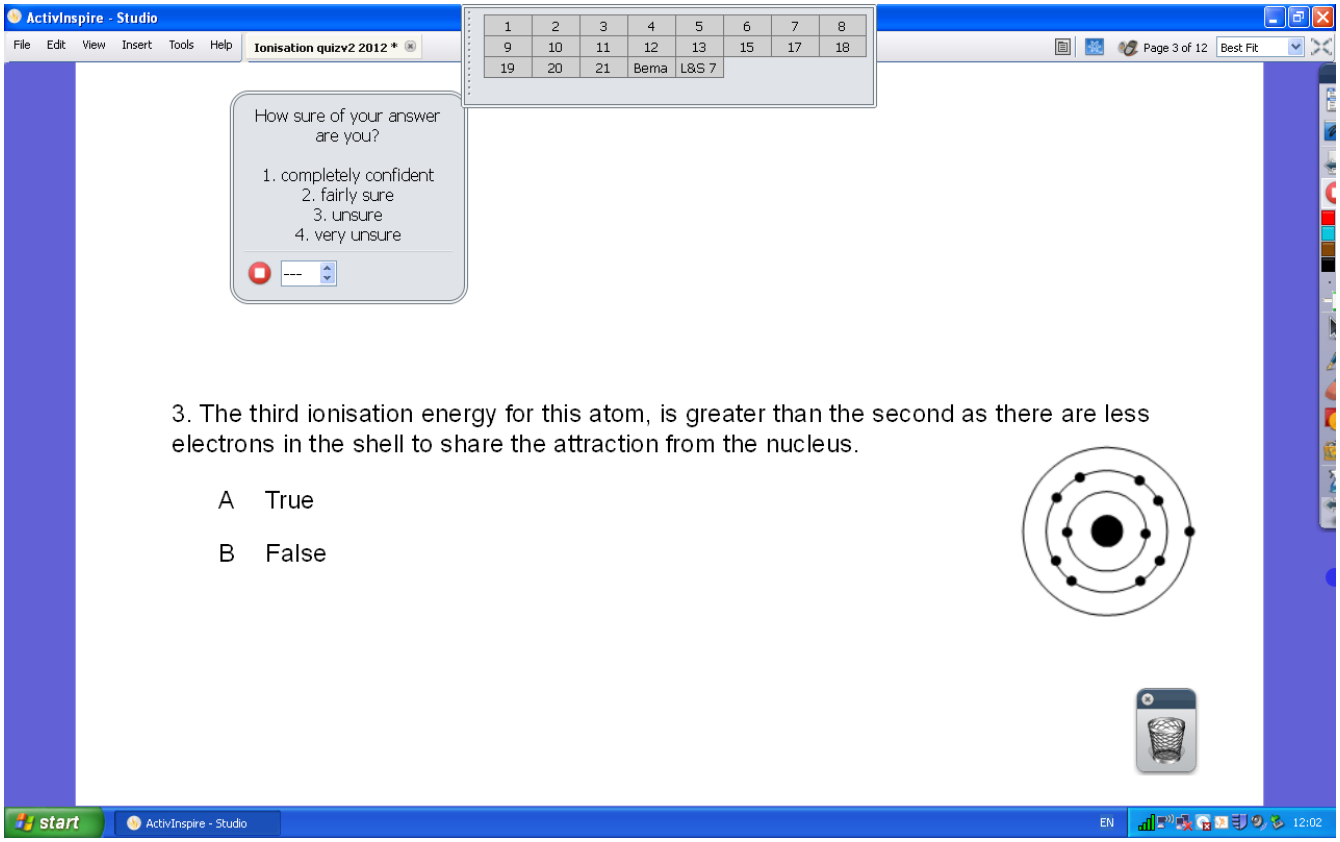


Table 1 shows only the statements used to probe electrostatic understanding and how they might reveal alternative ideas.

Question	Statements as they appeared on the screen with prompt for 'true or false' response by electronic voting (see fig. 1)	Alternative idea that might be indicated by a 'true' or 'false' response
3	The third ionisation energy for this atom is greater than the second as there are less electrons in the shell to share the attraction from the nucleus.	True: Attraction between nucleus and a particular electron varies according to how many electrons are present
4	Each proton in the nucleus attracts one electron.	True: Attraction is between individual protons and electrons rather than the nucleus acting as a point charge.
6	After the atom is ionised, it then requires more energy to remove a second electron because once the first electron is removed the remaining electrons receive an extra share of the attraction from the nucleus.	True: The nucleus charge can direct its attractiveness according to the number of electrons (not in keeping with Coulomb's law).
9	The eleven protons in the nucleus give rise to a certain amount of attractive force that is available to be shared between the electrons.	True: The nucleus charge can direct its attractiveness according to the number of electrons (not in keeping with Coulomb's law).
12	The third ionisation energy for this atom is greater than the second because the third electron is nearer the nucleus	False: Orbital or shell contraction due to reduced repulsion between fewer electrons is not noted as the cause of the increase in ionisation energy

Table 1:True/False Statements probing electrostatic ideas

The electronic questionnaire was administered at the beginning and end of a half day session focusing on explaining ionisation energy. In between the PSTs observed a demonstration with explanation and in groups they discussed an analogy. These form the intervention activities considered here.

Intervention activities

1. *Demonstration and Explanation:*

Given that causal explanations of ionisation energy depend on electrostatic ideas a Van de Graaff generator was used to model the simultaneous effects of attraction and repulsion to account for 'Shielding' and to demonstrate its electrostatic character. Fig 2 shows the detail of the demonstration set up. The charged hair (nucleus) moves when oppositely charged strip 2 is moved modelling the attraction between outer electrons (strip 2) and the nucleus in an atom. When charged strip 1(inner electrons that repel the outer ones) is removed the effect

the same motion has on the charged hair is greater (less shielding).

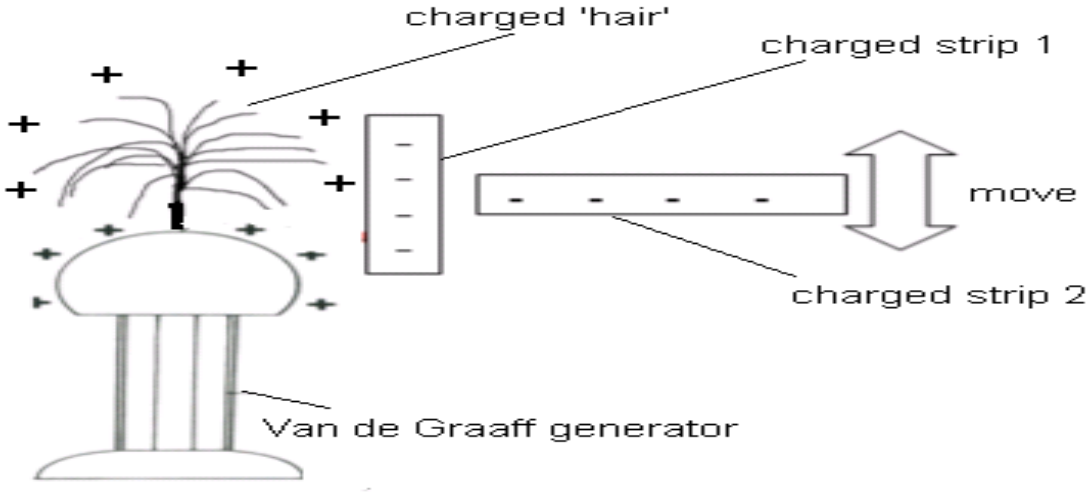
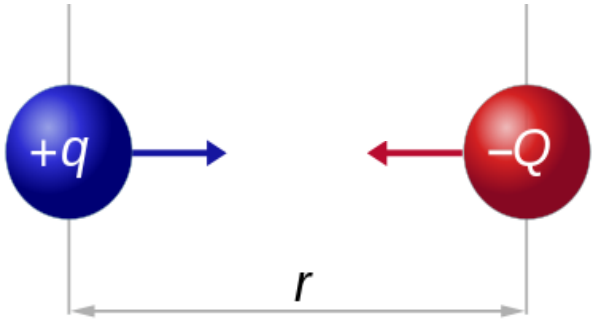


Fig. 2:Demonstration set up

Also Coulombs law was reviewed and applied to the atom – so that the charge on each electron (-Q) and the charge of the nucleus (+q) could be recognised as unchanging in terms the interaction between them for a specific atom (Fig.3):



$$F = k \frac{|q \times Q|}{r^2}$$

Fig. 3: Coulomb's law

2. Bonfire Analogy:

Tan *et al.* (2008) suggests that using a Bonfire analogy also helps support the idea that the attraction at a fixed distance between nucleus and a particular electron remains the same regardless of the number of electrons at the same distance. Given the difficulties noted when using analogies without fully acknowledging the target / analog match, this activity guides thinking about when the heat felt by people from the bonfire does and does not usefully map on to the target nucleus and electron electrostatic properties Treagust *et al.*(1998). The first task is to consider how the number of people present at the same distance away from the

bonfire affects the heat each one experiences, and then to use this analogy to explain the attraction between nucleus and an electron (see task details Fig. 4).

We can compare the attraction an electron experiences to the heat one receives from a bonfire.

The Bonfire heat experienced is dependent on:

- How big the bonfire is
- The distance one is away from the bonfire
- whether one is blocked (screened/shielded) from the bonfire

Tasks

1. **Consider the affect of how many people are present at the same distance away from the bonfire on the heat experienced.**
2. **Use this analogy to explain the attraction between nucleus and an electron.**
3. **Construct a table to explain the key parts of the analogy and note when the analogy breaks down.**

Fig. 4: Bonfire Analogy task materials

The final part of the task asks PST to review the target/analog features of the solar system atom analogy and then use this approach to examine the usefulness and limitations of the bonfire analogy (An example of this type of analysis is shown in Table 2).

Interviews:

In order to elicit pre-service chemistry teachers' explanations about ionisation energy values and particularly to explore the ideas draw upon, semi-structured interviews were used. Individual interviews of approximately 25 min each were conducted. The pre- intervention interviews were conducted from November 2011 to early February 2012.
These interview protocols consisted of questions probing four areas:

1. A graph showing the variation in subsequent ionisation energy values for an oxygen atom (pre-intervention) and a Fluorine atom (post intervention) were used to elicit an explanation for the variations
2. Pre-service chemistry teachers were asked to sketch and explain any visualisations that they drew upon during their explanations.
3. Atomic representation diagrams ((A) Rutherford type, (B) Electron cloud micrograph, (C) Bohr type and (D) Schrödinger type) were used as stimulus materials to explore the pre-service teachers' ideas about the atom and these representations of it. This allowed the pre-service teachers' use of the key terms; orbital, shell and energy level, to be clarified in relation to the atomic model features represented.
4. Pre-service teachers were asked to indicate which representations were useful for their explanations and how they were helpful.

The intervention occurred in mid February and the Post-intervention interviews occurred between April and June 2012. In the post intervention interviews PST were not asked to repeat part 3 & 4 of the above protocol but rather they were asked if and how the intervention activities had been useful in forming their explanation given at the start of the interview.

	Analogy (Bonfire)		Target (attraction between nucleus and an electron)	
	Feature	**Relationship**	**Feature**	**Relationship**
Shared attributes	The Size of the bonfire/ heat received	The larger of the bonfire greater the heat received by each person from it.	Nuclear charge/ attraction between electron and nucleus	The larger the nuclear charge the greater the attraction between electron and nucleus.
	The distance between bonfire and person	The greater the distance the smaller the heat received. The heat received by each person at the same distance is independent of the number people at that distance.	Distance between electron and nucleus	The greater the distance between electron and nucleus the smaller the attraction between electron and nucleus. The attraction between electron and nucleus is independent of the number of electrons at the same distance from the nucleus.
	Screening of the fire (by people nearer)	The more people screening the fire the less heat received.	Shielding	The greater the number of inner electrons shielding the less the attraction between shielded electrons and the nucleus.
Unshared attributes	Heat from people	The bonfire does not receive equal heat from people.	Attraction between nucleus and electron	Equal mutual attraction between nucleus and electron.
	Heat from people	People do not radiate heat equally nor is it dependent on size.	Repulsion between electrons	Mutual and equal repulsion between each electron (as charge is the same).

Table 2 shows the attributes that can be considered using this analogy.

Sample:

A convenience sample of 38 chemistry PSTs (full cohort of 50) were those present at two sessions (the same session repeated on the same day) which formed part of their initial teacher training course. All gave their permission for the anonymous collection and use of their responses to the electronic questionnaires. Six of these PSTs agreed to be interviewed prior to and after the PGCE session were all approached by email and gave permission for their responses to be audio recorded and extracts taken from these and from their drawings.

ANALYSIS

Analysis of data from T/F electronic questionnaire:

Confidence levels provided with each ‘true’ or ‘false’ response were used to allow the ‘guessing’ factor to be identified and accounted for. Using a framework developed from Khan, Davies & Gupta’s (2001) any responses which indicated ‘unsure’ character were considered as ‘guessing’ regardless of correctness of response and only the confident correct or incorrect responses used as indicators for assigning a good understanding or use of alternative ideas. Table 3 shows this framework.

Knowledge indicated by the response	Correct				Incorrect			
Level of confidence in response	completely confident	fairly sure	unsure	very unsure	very unsure	unsure	fairly sure	completely confident
General confidence	sure		unsure		unsure		sure	
Concept grasp as indicated from the response and confidence	Good concept		Guessing				Alternative idea	

Table 3: Framework showing the relationship between confidence and accuracy of true false responses.

In order to consider the efficacy of the activities the change in response to the questions was evaluated. Favourable outcomes would be indicated by improving concepts and maintenance of good concepts already held. Unfavourable outcomes would be indicated by continuing to guess or give alternative idea responses and particularly undesirable outcomes would be the potential introduction of alternative ideas or confusion. Table 4 links these possible changes to the categorisation of response changes from the electronic questionnaire.

Response shift	Alternative idea to good concept	Guessing to good concept	Alternative idea to guessing	Remains with good concept	Remains guessing	Remains with alternative idea	Moves from guessing to alternative idea	Moves from good concept to alternative idea
Change in conception	Alternative idea address	Good concept developed	Alternative idea challenged	Good concept not shaken	Confidence is not developed	Alternative idea is not challenged	introduction of alternative idea	introduction of alternative idea
General effect	Improving			Remains good concept	Remains guessing or with alternative idea		Potential introduction of alternative idea	
Effect of activities	positive			No effect on good concept	No effect on guessing or alternative ideas		Negative	

Table 4: Summarises these potential shifts in responses

Analysis of interview data:

Interview responses were analysed to characterise the types of explanations and the types of atomic visualisations used. The coding and categorisation methods used in the earlier study with a larger interview sample were used again Wheeldon (2011). Content analysis of the data looked for causality arguments. Commonly, when describing the effect of distance from the nucleus on ionisation energy values, 'closer' or 'nearer' or their opposites were used and all these linked with appropriate variation in electrostatic attraction was quite accurately used to form appropriate similar causal arguments. These similar terms were all coded 'D' for 'distance'. These then could be linked with coding for the nucleus or core etc 'N' and with electrostatic attraction terms (ESA). Together these terms and the linkages between them could then identify the causal ideas used. The researcher and a further advanced level chemistry teacher categorised explanations in this way and a high level of inter-rater reliability determined.

FINDINGS

Forty nine percent of response changes to all statements were positive. 20% indicated an unchanging scientific concept was used to respond. However 12% of response changes were negative. If this is considered rather in the net effect on an individual PST via their changes in response to the six statements then the data indicates that for 82% of PSTs (31 of 38), these activities are effective in supporting the development and retention of electrostatic principles applied appropriately to the atom, to allow causal arguments to be used to explain ionisation energy values. For four PSTs (10%) these interventions appear to have an overall negative effect. (Fig.5)

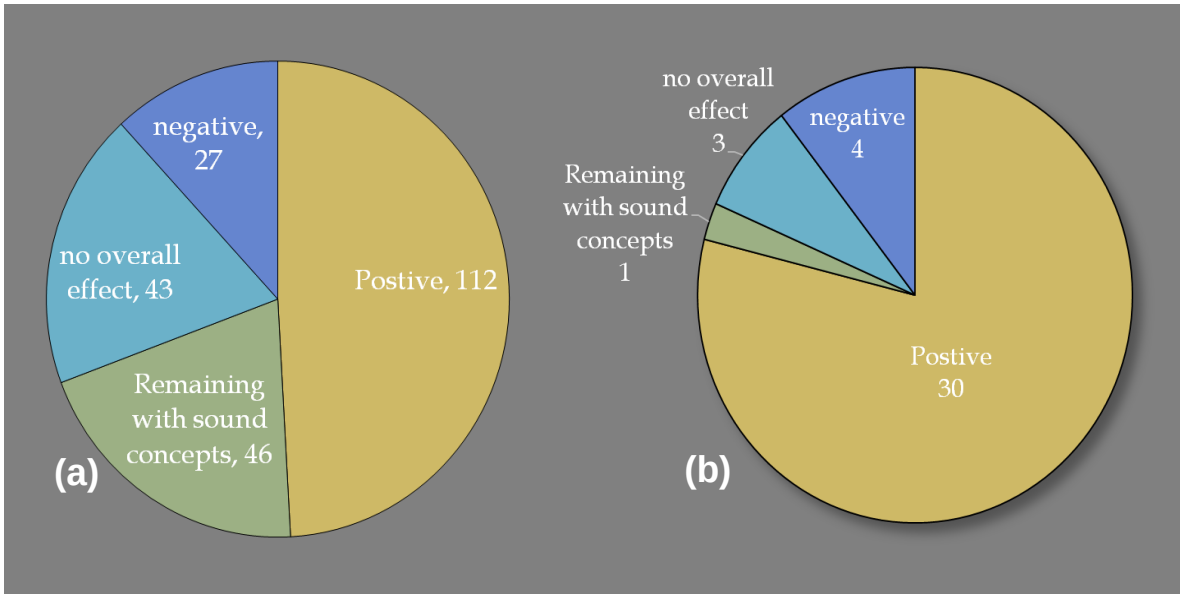


Figure 5: Response changes (a) for all statements, (b) overall for each PST

Table 5 shows the electrostatic ideas used by those interviewed alongside those indicated by the electronic questionnaire responses before and after the intervention activities. The interviews also indicate that for all 6 PSTs the causal ideas used are either maintained or improve. This broadly mirrors the general trend of using more causal electrostatic ideas and less non scientific ideas about these interactions.

Table 5: Ideas used to explain ionisation energy before and after intervention activities drawn from electronic questionnaire and interview data.

	Ideas used to explain ionisation energy **prior to** intervention activities (I – from interview, EQ- from electronic T/F quiz)										Ideas used to explain ionisation energy **after** intervention activities (I – from interview, EQ- from electronic T/F quiz)										Effect of intervention	
	Non causal electrostatic ideas					Causal electrostatic ideas					Non causal electrostatic ideas					Causal electrostatic ideas						
						using attraction				using repulsion						using attraction				using repulsion		
PST (pseudonyms)	the nuclear charge is shared out over electrons/ imbalance of numbers of electrons compared to nuclear charge or nuclear charge is directed to particular electrons					electrostatic attraction affected by spatial distribution of electrons		shielding related to electrostatic attraction / spatial distribution of electrons		electrostatic repulsion effected by spatial distribution of electrons	paired electrons connected to repulsion	the nuclear charge is shared out over electrons/ imbalance of numbers of electrons compared to nuclear charge or nuclear charge is directed to particular electrons					electrostatic attraction affected by spatial distribution of electrons		shielding related to electrostatic attraction / spatial distribution of electrons		electrostatic repulsion effected by spatial distribution of electrons	paired electrons connected to repulsion	Change in the frequency of alternative ideas and good explanatory ideas used	Change in overall responses
	I[b]	EQ[a]				I[b]	EQ[a] 12	I[b]	EQ[a] 7	I[b] only		I[b]	EQ[a]				I[b]	EQ[a] 12	I[b]	EQ[a] 7	I[b] only		I[c]	EQ[c]
		3	4	6	9								3	4	6	9								
Josephine		GC	GC	GC	GC	√	GC	√	GC	√			GC	GC	GC	GC	√	GC	√	GC		√	RGC	RGC
Anna	√	G	GC	AI	AI	√	AI		G		√	√	GC	GC	GC	GC	√	GC		G			N	P
Louise	√	AI	GC	AI	G	√	AI	√	GC			√	G	GC	G	G	√	G	√	GC			NE	P
Ahmed	√	G	G	G	G	√	G		M				GC	AI	G	AI	√	G	√	G			P	NE
Mary		G	G	AI	AI	√	AI		GC	√	√		GC	GC	GC	G		G	√	GC	√	√	P	P
Karen		G	G	G	G	√	AI		G	√			GC	G	GC	GC	√	G	√	AI	√	√	P	P

Foot notes: [a] AI – alternative idea shown by a confident incorrect answer, G- any answer with an unsure confidence level indicating guessing and GC – a confident correct answer indicating a good concept,

[b]- √ - use of ideas indicating an alternative idea, √ - use of ideas indicating a good conception held.

[c] –RGC – good concepts are retained, P – Positive effect- overall more good concepts are used or less alternative ideas shown NE – No effect- No change in the overall use of alternative ideas and/ or good conception ideas used. N –Negative effective overall less good concepts used and alternative ideas retained

Five of the six interviewed PSTs retain or improve the concepts that they use, compared to all six showing improvement, retaining or no change from their electronic voting data. The interviews were between a month and two months later than the interventions and thus one might expect a reduction in the long term retention of ideas used.

Limitations

As with all convenience samples, its very nature means that it is not necessarily representative of wider pre-service chemistry teachers. Another issue is that the interview and electronic questionnaire responses given are a 'snap shot' which cannot be assumed to be representative of a pre-service teacher's general thinking. In particular the interview data are formed from the meaning made from what was experienced and communicated in that interview context at that time.

CONCLUSIONS AND IMPLICATIONS:

The number of positive effect changes in response to the electronic questionnaire indicates that these activities are effective in supporting the development of electrostatic principles applied to the atom in order to allow causal arguments to be used to explain trend in ionisation energy values. However for a small number of PSTs these interventions appear to have a negative effect.

As teachers teach science as they understand it, they are likely to continue to pass on alternative and non causal electrostatic ideas to their pupils. The multiple effects of combined repulsion and attraction between electrons and nucleus in the atom examined here also result in chemical behaviours, and hence further clarification of these electrostatic principles as applied to the atom goes beyond this ionisation energy context and thus supports a deeper understanding more generally.

It is clear therefore that pupils and their teachers need further support in modelling coulombs law with respect to the atom. A successful approach would include these aspects:

a. Review Coulomb's law and how electron distribution is represented in different atomic models;
b. Explicit application of these electrostatic principles (often already known) to the charge distribution due to electrons and nucleus in atoms. Demonstrations similar to that above showing the effect of repulsion between negative charges on the effective interaction between outermost negative charge and the positive one.
c. Encouraging students to examine their atomic visualisations that they use forming explanations to ensure that they are able to appropriately model both repulsive and attractive characteristics.

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