ELECTRONS AND ORBITALS: CHALLENGES AT FIRST YEAR LEVEL AND BEYOND

Liliana Mammino,
Department of Chemistry, University of Venda, South Africa
E-mail: sasdestria@yahoo.com

Abstract
Our description of atoms is governed by quantum mechanics. The most important results presented to chemistry students well before they encounter quantum mechanics are those concerning electrons. However, the description in terms of orbitals and quantum numbers appears to pose considerable challenges to students. Learning difficulties like poor language-mastery and misconceptions inherited from previous instruction bring additional complications. Careful attention to students' difficulties, and to their responses to the teaching approaches utilised, becomes the key to the design of explanation options aimed at facilitating conceptual understanding.

The paper provides an overview of 15-year direct experience in this regard in the first year general chemistry course at the University of Venda, involving continuous interplay between systematic diagnoses of students' difficulties and redesign of teaching approaches to better address them. It is concluded that interventions at pre-university level, in terms of attention to rigour and development of language-mastery, would be crucial to improve students' performance.

Keywords: Atomic orbitals, electrons, language-related difficulties, language-mastery, quantum numbers.

1.1. INTRODUCTION

Chemical systems and phenomena are explained in terms of molecules and what molecules do. The importance of familiarising students with the molecular level since their first approach to chemistry has been recognised for many decades. It has further increased in recent times, after the progress in the computational study of molecules has enormously expanded our ability to relate the behaviour of substances to the properties of their molecules and also to predict the properties of not yet synthesised substances.

Molecules are made of atoms. Therefore, learning about atoms is prerequisite to learning about molecules. The world of atoms and molecules is governed by the uncertainty principle and by the relevance of the wave-particle duality and, therefore, is described by quantum mechanics. Since the basic results are essential for the interpretation of chemical phenomena, they need to be presented to chemistry students well before they encounter quantum mechanics; they are then presented in purely descriptive terms.

Although molecules are more complex systems than individual atoms, it is possible to present molecules in an easier way through visualizations like ball-and-stick or space-filling models, which are apt to transmit fundamental information, such as the sequence in which atoms bond to each other, the fact that molecules have a 3-dimension structure, or the preferred geometries of a given molecule. This favours the generation of mental images – which is recognised as particularly important for conceptual understanding in the physical sciences (Harre, 1970).

The case of atoms is more challenging. Their structure is described in terms of electrons, orbitals and electron configurations – a description that appears to pose considerable challenges to students, up to the point that some authors had proposed to avoid it altogether as "too abstract". However, "*it would be wrong to omit discussions of the inductive approach of Mendeleev and the deductive approach initiated by Schrödinger, because they compose the consummate example of that interaction of empirical and rational epistemologies that defines how chemists think*" (Richman, 1998). Basic information about electrons is essential (Mammino, 2008) because chemical phenomena depend on what electrons do. The quantum mechanical description of atoms and molecules has acquired new practical (industrially relevant) importance because of its role for the design of new substances (including drug design) and for the expanding field of nanotechnology. This increases the importance of familiarising students with the main concepts since their first encounter with chemistry (Mammino, 2008).

Visualization has less ability to provide mental images in the case of atoms than in the case of molecules. As an overall system, an atom can only be visualised as a sphere. Orbitals can be visualised through their shapes (i.e., through the polar diagrams related to the angular dependence of the probability density). However, they can be visualised one at a time. It is not easy to design a model simultaneously showing all the occupied orbitals in an atom. Electron configurations can be visualised through symbolic diagrams; however, direct experience shows that the purely symbolic character of these representations is not always recognised by students and they risk to be translated into physical representations (e.g., in terms of boxes inside an atom). Altogether, visualisation is not adequate to convey a realistic perception of the structure of the atom or the nature of electrons.

In the face of all this, the major educational challenge is designing approaches to convey information that remains rigorous while being adapted to the characteristics and needs of specific groups of students. The task requires prior identification of those characteristics and careful attention to students' responses, to prevent possible misinterpretations. The current paper focuses on how this has been done at the University of Venda (UNIVEN, a historically black university located in a rural area in South Africa). It reports observations (with extensive documentation to support analyses and inferences), outlines the interplay between diagnostic observations and design of teaching approaches, and presents inferences on the need to address problems at pre-university level.

1.2. BACKGROUND INFORMATION

A systematic study of the difficulties experienced by UNIVEN chemistry students has been carried out in the last 15 years (Mammino, 2010 and references therein), with the objective of utilising diagnoses to improve teaching approaches. The study highlighted major problems such as: generalised underpreparedness; poor language-mastery (both in general logic/linguistics terms and in terms of poor mastery of the second language that is the medium of instruction); poor mastery of other relevant learning tools, including visual literacy; misconceptions inherited from previous instruction. These problems impact heavily on the effectiveness of teaching and learning activities. The impact is even greater for themes – like the structure of the atom – that do not have familiar correspondences in direct experience. The poor language-mastery poses drastic restrictions to the possibility of elaborating on concepts and models, because it hampers students' possibility of following discourses with articulation-degree beyond the most basic. All this determines the necessity to search for options providing a reasonable compromise between two important needs: maintaining acceptable standards at content level and ensuring that as many students as possible access the information offered in a course. The author has opted to focus on the concepts that are necessary to build a correct – although basic – picture, and to put ample emphasis on each of them. For the first year general chemistry course, the concepts include: the nature of the electron and how we can (or cannot) imagine it, including the fact that we cannot speak of *position* for an electron in an atom; the quantisation of the electron's energy in the atom; the meaning of orbitals; the roles of quantum numbers; the spin as a property of elementary particles; electron configurations of atoms and their relationship with elements' positions in the periodic table. Extensive clarifications of non-rigorous conceptions inherited from previous instruction are incorporated as integral components of explanations.

Diagnoses across years have also determined major changes in the assessment options for this course, following changes in the characteristics of incoming students. In the early 2000s, a reasonable proportion of students could provide basic answers to questions requiring descriptions or explanations. In more recent years, the sharp decrease in language-mastery has sharply decreased the ability to build sentences to describe objects and phenomena, up to the point that most students would fail to write sentences or sets of sentences conveying an understandable meaning (at least, in English). In order to reduce penalisations for language-related difficulties, the author opted to resort to multiple-choice questions for those themes that are particularly challenging from a conceptual point of view (and, consequently, also from an expression point of view), because understanding the meaning of a written sentence is easier than building a sentence in one's own words. The themes include all the aspects related to atoms and molecules. The design of entries for multiple-choice questions closely relates to the aspects that are emphasised in lectures and tutorials, so that assessment responds to what has been directly offered to students. Although this renounces the possibility of checking students' abilities to personally elaborate on acquired information, it was considered a tolerable necessity for the first year level, whose main objective is to build conceptual and skills foundations.

Although poor language-mastery has been the determining reason for the selection of the just-described pedagogical options, space constraints do not allow detailed presentation of how it impacts on science learning. It can be mentioned that the findings outlined in (Mammino, 2010) are consistent with the results of many other studies. General language-mastery (the mastery of the basic features of the logic of expression-through-language) has fundamental importance for science learning, as understanding concepts depends on understanding the language through which they are expressed (Munby, 1976; Carré, 1981; Davies & Green, 1984; Muralidhar, 1991; Sutton, 1992; Wellington & Osborne, 2001; Norris & Phyllis, 2003; Fang 2006; Brooks, 2006). Second-language instruction enormously increases understanding difficulties (Benson, 2004; Alexander, 2005; Brock-Utne & Hopson, 2005; Brock-Utne & Skattum, 2009; Heugh, 2009; Mammino, 2011a), and the impact is even greater when inadequate mastery of the theory of the mother tongue prevents learners from attaining adequate mastery of the second language (Qorro, 2011). In South Africa, inadequate language-mastery also relates to frequently unsatisfactory standards of pre-university instruction (Reddy et al, 2006; Fleisch, 2008; Heugh, 2009; Mtshali & Smillie, 2011) and is a major responsible of the epistemological-access deficiencies of many students entering universities (Mammino, 2012).

1.3. DATA AND ANALYSIS

1.3.1. Information sources and analysis criteria

The author considers the answers provided by students in their curricular work (tests and lab reports) as the most reliable sources of information because they correspond to the occasions in which students put maximum efforts to produce their best. Students' answers are compared on marking, to identify problems that need clarifications in class, recurrence patterns, and indications about explanation approaches. Answers considered particularly representative are recorded. The analysis of answers integrates conceptual and language points of view, as outlined in (Mammino, 2005). Selection-totals for the entries in multiple choice questions are also recorded. Information of this type has been systematically collected throughout the last 15 years (collected for each test and lab report, currently reaching a cumulative total of several thousands). It thus reflects also the changes associated with changing background-preparation of incoming students. The large number of students in the first year group confers statistical value to the corresponding observations.

The information from written works is complemented by students' answers during classroom interactions, particularly revealing about pre-existing misconceptions or on-the-spot misinterpretations of the concepts discussed. Personal interviews have been occasionally utilised, above all to try and identify possible causes of diagnosed difficulties.

1.3.2. Information from students' own sentences

Answers in which students write their own sentences have broad-spectrum information-ability, highlighting a large variety of difficulties (including language-related difficulties) and misconceptions. Space constraints prevent reporting the questions appearing in all the tests and tutorials throughout the years concerned, or representative answers for each year. Some examples from the year 2000 are selected, to offer a representative sampling of more recurrent difficulties; they are reported exactly in the students' words.

Answers 1–13 concern the explanation of the meaning of *energy level*. Answers 1 and 2 are sufficiently clear and conceptually sound. Answers 3–10 reveal the perception of energy levels as physical spaces, often with additional misconceptions (e.g., the permanence of the orbits model in the modern description of the atom). Answers 11–13 fail to convey a meaning, because of the way in which words are combined (Mammino, 2007).

1. *The value of allowed energy state of an electron in an atom.*
2. *The energy which is discrete and quantised is called energy level.*
3. *Levels which are filled by an electron in the orbitals of an element.*
4. *The highest energy levels among the others. Energy level is the level in which electrons are kept.*
5. *The space in which elements are arranged with increase in energy from low to high electronegativity element.*
6. *The place where the electrons is going to occupy when filling the electrons configuration of an atom.*
7. *Space around the nucleus which consists of orbits.*
8. *Level of the orbitals where the orbitals move around the nucleus in circular orbits.*
9. *The electron-carrier in the nucleus of an atom (i.e., orbitals are contained here).*
10. *The level of an atom at which electrons are found.*
11. *The external energy of the orbital.*
12. *A level in which an electron can occupy.*
13. *The way in which the energy levels occupy in the atom.*

Answers 14–18 refer to how electrons occupy atomic orbitals. Even when they express correct pieces of information, the answers are never exhaustive, but consider only one of the criteria. The first part of answer 14 recalls that electrons occupy orbitals in order of increasing energy (the second part is meaningless). Answer 15 highlights a typical language problem: the "in order of increasing energy" concept is reworded into the expression of an objective (*in order to increase*). Answers 16 and 17 refer to Pauli's exclusion principle, but their wording transfers the "being different" quality to the electrons or to their charges (whereas all electrons are identical and have identical charge; only their spins may differ). Answer 18 refers to Hund's rule about degenerate-orbitals filling. Both answer 17 and 18 indicate the image of arrow-shaped electrons (an image born from ascribing physical reality – in terms of shape of particles – to the arrows used to denote the spin vector).

14. *Starting from the lowest energy level. The orbitals must not "disturb" the energy level.*
15. *The electron occupy the energy level in order to increase the number of atomic orbitals.*
16. *Orbitals are occupied by two different electrons on different directions.*
17. *Electrons in each orbital should have different charges and different positions, the one is facing up, the other one has to face down.*
18. *The orbitals must complete the orbitals pointing upwards and followed by the ones pointing downwards.*

Answers 19–23 refer to the meaning of electron configuration. The proportion of reasonable answers (e.g., 19) is considerably larger than for the previous questions; however, the proportion of incorrect or meaningless answers (e.g., 20–23) remains worrying.

19. *The set of orbitals occupied by electrons in a given atom.*
20. *The set of all orbitals of the atom in the nucleus.*
21. *Set of orbitals occupied by electrons in nucleus.*
22. *Set of orbitals which occupied by electrons in the external energy.*
23. *It gives us information about how nucleus occupy the electrons.*

The answers show that, although better than in recent years, language-mastery was often insufficient for the expression of concepts. Thus, they also corroborate why, as the proportion of answers with no literal meaning or with absurd meanings increased in subsequent years because of further language-mastery decline, it became necessary to resort to assessment forms in which students are not asked to write their own sentences, but select conceptually correct statements from a set of proposed entries.

1.3.3. Information from students' selections from sets of proposed statements

As already mentioned, the statements proposed for students' selection in multiple choice questions are closely related to the concepts emphasised in the class, including attempts to correct diagnosed misconceptions or misinterpretations. The misconceptions that are objects of thorough discussion include the idea that electrons have the shape of arrows; the image that the spin relates to the electron rotating about its axis (incorrect, because the electron in the atom is largely a wave, and a wave does not rotate on itself); the idea that orbitals are sort of boxes inside the atoms (sometimes perceived as the "rooms" where electrons stay, in a hostel-like image of the atom); the idea that *orbital* has the same meaning as *orbit*; and various others. Many entries appear recurrently in various years, because of the need to emphasise fundamental concepts. The entries utilised in recent years are reported in table 1, and an overview of students' selections is shown in table 2. In both tables, the correct entries are identified by a small sphere (•) following the letters denoting them. In the actual questions, each set of entries is preceded by a statement setting the context, such as “consider the modern model of the atom”, “consider atomic orbitals”, “consider the quantum numbers characterising atomic orbitals”, etc.

All the questions are discussed in post-test sessions, trying to engage students in active analysis of why certain entries are not correct, in line with the pedagogical significance of error analysis (Love & Mammino, 1997). Despite the emphasis devoted to these major aspects in pre- and post-test sessions, the persistence of the conceptions formed at the first encounter with a certain theme appears to be overwhelming. An impressive example is the huge proportion of students selecting entry F (“an atomic orbital is a circle along which the electron is moving”) in test 13 (table 2), despite repeated explanations and discussions on the difference between the *orbit* and *orbital* concepts, supported also by visualization (drawings on the board). This unequivocally underlines the importance of providing rigorous concepts and images since the beginning, conferring it a character of pedagogical urgency.

1.3.4. Information from the application level

In a general chemistry course, the application level of the information about the atomic structure comprises writing the electron configuration of a given atom and the ability to

Table 1
Set of entries utilised in the past years in multiple-choice questions on electrons and atomic orbitals.
The first column reports the letter with which each entry is denoted, the second column reports the entry as it appears in the questions given to students.

letter	entry
A	the energy of the electron in the atom can take any value
B•	the energy of the electron in the atom can take only certain values
C	we can identify the position of an electron in the atom at any time
D	the electron spins about its axis like the earth spins about its axis
E	electrons have a spin quantum number because they spin about their axis
F	an atomic orbital is a circle along which the electron is moving
G•	we visualize atomic orbitals as regions around the nucleus in which the probability of finding the electron is high.
H	atomic orbitals are like boxes inside an atom, where the electrons are located
H1	the p orbitals are three consecutive boxes (three boxes attached to each other)
I	the principal quantum number of the s orbitals is 1

J	quantum number l can take all the integer values between –n and +n
K	quantum number m_l can take all the integer values between –n and +n
L	when n = 4, the angular momentum quantum number can take the values 0, +1, +2, +3 and +4
M•	the energy of the electron in a certain orbital is determined by quantum numbers n and l
M1	the energy of the electron in a certain orbital is determined by quantum number m_l
N	the shape of the atomic orbitals is determined by quantum number n
N1	the shape of an atomic orbital is determined by quantum number m_l
O•	the orientation in space of an atomic orbital is determined by quantum number m_l
O1	the orientation of an atomic orbital in space is determined by quantum number l
O2	the orientation of an atomic orbital in space is determined by quantum number n
P•	atomic orbitals are degenerate if they have the same quantum numbers n and l and different m_l
Q•	the number of degenerate orbitals with the same quantum numbers n and l is equal to the number of possible values of quantum number m_l
R	the 3p atomic orbitals have n = 3, l =3 and m_l = –3, –2, –1, 0, +1, +2, +3
R1	the 3p atomic orbitals have n = 3, l =2 and m_l = –2, –1, 0, +1, +2
R2•	the 3p atomic orbitals have n = 3, l =1 and m_l = –1, 0, +1
S•	there are three p atomic in the energy levels with n ≥ 2 because there are three possible values of quantum number m_l when l = 1
T	the 3d atomic orbitals have n = 3, l =1 and m_l = –1, 0, +1
T1	the 3d atomic orbitals have n = 3, l =2 and m_l = –1, 0, +1
U	there are five d orbitals because their quantum number l is 5
V•	there are no d orbitals in the second energy level because quantum number l can only take the values 0 and 1
W	p atomic orbitals correspond to m_l = 2
X	f atomic orbitals correspond to l = 2
Y	two electrons occupying the same orbital must have parallel spins
Z	electrons occupy all the orbitals with n = 4 before starting occupying orbitals with n = 5

Table 2
First year students' selections in multiple-choice questions concerning electrons and orbitals.

The "test #" column ascribes a number to each test to facilitate references to it. The "entr" column reports the letter denoting the entries selected for the given question, as listed in table 1.

The "year" column specifies the year in which the question was given. The "ans" column reports the number of students selecting the given entry, and the % column reports the corresponding percentage relative to the sum of the selections for the given answer (the sum is very close to the number of students writing a given test, because the number of students not providing an answer is negligible).

test #	year	entr	ans	%	test #	year	entr	ans	%	test #	year	entr	ans	%
1 [a]	2007	F	77	27.5	6	2011	M1	44	16.2	11	2013	N	92	18.5
		A	55	19.6			N1	34	12.5			N1	79	15.9
		M•	132	47.1			O•	75	27.6			Q•	224	45.1
		C	19	6.8			J	56	20.6			O1	59	11.9
		Q•	58	20.7			K	63	23.2			O2	43	8.7
		D	36	12.9										
		N	101	36.1										
2	2008	G•	69	46.9	7	2011	G•	109	42.6	12	2013	R	114	22.9
		H	11	7.5			F	45	17.6			R1	184	37.0
		H1	19	12.9			H	5	2.0			R2•	153	30.8
		U	10	6.8			H1	50	19.5			T	17	3.4
		I	38	25.9			I	47	18.4			T1	29	5.8
3	2008	F	52	27.2	8	2012	N	47	13.5	13	2013	V•	142	29.3
		B•	85	44.5			Z	48	13.8			N	103	21.3
		A	10	5.2			R	45	12.9			F	204	42.1
		C	17	8.9			R1	102	29.2			X	11	2.3
		D	27	14.1			R2•	107	30.7			H	24	5.0
4	2008	M1	28	14.2	9	2012	F	92	29.6					
		N	56	28.4			H	24	7.7					
		Q•	72	36.5			N	97	31.2					
		J	18	9.1			S•	82	26.4					
		K	22	11.2			W	16	5.1					
5	2011	P•	78	28.4	10	2013	F	159	32.8					
		Z	70	25.5			A	20	4.1					
		L	39	14.2			C	14	2.9					
		E	41	14.9			M•	235	48.5					
		Y	47	17.1			D	57	11.8					

[a] In this case the sum of the percentages is not 100 because of the simultaneous presence of two correct answers.

recognise correct sets of quantum numbers on the basis of their possible values (n = 1, 2 ...; l = 0, 1 ... n – 1; $m_l = -l \ldots 0 \ldots +l$).

Independent writing of electron configurations highlights a huge variety of difficulties. For instance, only 85 out of 359 students wrote a correct electron configuration for mercury in a 2012 test. The errors included: not proceeding beyond the lowest energy levels (answers terminating after 4s or 4p); incorrect filling of orbitals (e.g., 4 or 14 electrons in inner p-type orbitals); the introduction of non-existing orbitals (e.g., 3f); limiting the orbitals only to s-type and p-type (so that the answer ends with $9s^2 9p^6 10s^2 10p^6 11s^2 11p^4$ or the like); and what appears a deliberate refusal to consider the orbitals in order of increasing energy, filling them in the sequence 1s 2s 2p 3s 3p 3d 4s 4p 4d 4f 5s 5p 5d 5f ...

Multiple-choice questions also include requests to select a correct electron configuration from a proposed set. The number of students selecting correct entries is much higher than the number of students writing correct electron configurations independently. The selected correct entries relative to the total number of answers were 185/280 and 172/280 for the two correct entries in a 2007 test; 156/201 in 2008, 185/277 in 2011, 233/316 in 2012, 307/502 and 344/489 in two occasions in 2013. Table 3 shows the proportions of students who selected the various types of incorrect entries in these same tests.

Table 3
First year students' selections in multiple-choice questions concerning electron configurations.
The first column lists the types of errors inserted in the entries of multiple-choice questions. The columns titled "selected" show the proportion of answer selecting a certain entry, relative to the total number of answers to the given question. The columns titled "year" states the year; double mention of the same year indicates two questions of the given type, on different occasions.

Type of error	selected	year	selected	year	selected	year
Incomplete filling of an orbital before filling the next (e.g. $5s^2 4d^8 5p^6$)	25 / 280	2007[a]	22 / 277	2011	38 / 502	2013
	20 / 201	2008	8 / 316	2012	17 / 489	2013
Exceeding the number of electrons for the given orbital (e.g., $4p^7$, $3d^{14}$)	24/316	2012	25/489	2013		
Grouping orbitals with the same n (e.g., $3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 4f^{14} 5s^2 5p^6 5d^{10}$)	9/201	2008	16 / 316	2012	42/489	2013
	27/277	2011	50/502	2013		

Errors in the orbitals after 6s (e.g., $6s^2 6d^7$ or $6s^2 4f^{14} 6d^4$)	36/280	2007 [a]	43/277	2011	69/502	2013
	16/201	2008	35/316	2012	61/489	2013
Including non existing orbitals (e.g., 2d)	33/280	2007 [a]	38/502	2013		

[a] The 2007 question comprised 7 entries, with two correct ones.

Table 4
First year students' selections in multiple-choice questions concerning sets of quantum numbers.

Type of error	selected	year	selected	year	type of error	selected	year	selected	year
l = n	20 / 194	2008	211 / 490	2013	$l < 0$	13 / 194	2008	50 / 490	2013
l > n	22 / 194	2008	73 / 490	2013	$m_l > l$	22 / 194	2008		

Quantum numbers appear to be particularly challenging. The rate of correct answers to questions asking students to identify the quantum numbers of specific orbitals is often poor. E.g., 46 out of 141 answers to a question asking students to write the quantum numbers characterising the 4f orbital (2004) were correct, 14 students did not answer, and the other answers contained various errors, including errors in the identification of the principal quantum number n. Multiple-choice questions concerning the quantum numbers of specific orbitals appear likewise challenging (entries R, R1, R2, T, T1, W, X in table 1). The rate of correct answers is also poor for questions dealing solely with quantum numbers and asking students to select correct combinations; table 4 reports the main types of errors included in the entries proposed in recent years, and the proportions of answers selecting each of them.

1.3.5. Beyond the first year

In the courses taught by the author at UNIVEN, a verification of difficulties with the atomic structure beyond the first year is possible in the first postgraduate (*Honours*) physical chemistry course (a quantum chemistry course). Diagnostic surveys, conducted in the initial part of the course through in-class written questions requiring short answers (Mammino, 2013), show high permanence-rate of conceptions formed in pre-university instruction, including the dominant mental image of the planetary model of the atom and the idea that electrons are arrow-shaped and spin around their axis. This confirms the nearly *imprinting* character of the images formed at the first encounter with a certain theme.

Difficulties at writing correct electron configurations, or answering questions on the roles and possible values of quantum numbers, resemble those diagnosed in the first year. Even after instruction (which involves detailed discussion of all the aspects related to the description of the atom), students find it difficult to answer questions like why there are three p orbitals whenever p orbitals are present, or why there are no 2d orbitals – all questions whose answers are based on the consideration of the possible values of the n, l and m_l quantum numbers. It may not be easy to comprehend how students who are already studying the Schrödinger equation and its solutions may experience difficulties with basic concepts. The only hypothesis that appears realistic ascribes these difficulties to the impact of passive memorization – a learning habit that students acquire in pre-university instruction and maintain as a way of circumventing language-related difficulties (memorising sentences as a surrogate to understanding them). Passive memorization does not produce mental impacts and, therefore, concepts are not retained. Furthermore, it does not develop the ability to relate different pieces of information or to derive inferences from acquired information.

1.4. DISCUSSION AND CONCLUSIONS

Diagnoses and analyses presented in the previous sections are contextual. The diagnosed difficulties are closely related to known learning problems of disadvantaged second-language contexts (references in section 1.2). The design of teaching options has tried to respond to diagnosed difficulties as closely as possible, by selecting only fundamental features, giving extensive consideration to each of them individually and utilising very simple sentences throughout. Although this approach may be limited, by not providing interesting expansions into more complex pictures, it responds to the objective of trying to generate a basis on which it may be possible to build further chemical knowledge.

Experiences in a non-disadvantaged context showed that the structure of the atom can be presented in a much broader way – incorporating more information typical of quantum mechanical approaches and results – even to younger (high secondary school) students, by designing ways of presenting advanced material in accessible descriptive terms (Mammino, 1994 and 2003). Students who were in a position to access such information pertained to a mother-tongue-instruction context and attended secondary schools where language-mastery development is given extensive attention (the Italian school system comprises different types of secondary schools, with different trends). This can be considered an additional confirmation of the role of language-mastery as the major key to conceptual understanding in the sciences.

In the case of UNIVEN students, the impact of poor language-mastery and of the frequent provision of non-rigorous information in earlier instruction is so dominant as to overshadow possible influences by other factors. The diagnosed permanence – even at advanced levels – of incorrect images, imprecisions and misconceptions inherited from pre-university instruction simultaneously highlights the difficulties of replacing the conceptions formed at the first encounter with a certain theme by other conceptions and the negative impact of passive memorization on knowledge-acquisition. Since passive memorisation is a habit inherited from previous instruction and is mostly retained because of the challenges posed by poor language-mastery, the observations also confirm the importance of enhancing students' language-mastery as the major key to build effective epistemological access (Mammino, 2012).

A major conclusion, already anticipated in previous sections, concerns the importance of providing correct information since learners' first encounter with atoms and molecules. The encounter mostly occurs in pre-university instruction. It would be interesting to verify the extent to which physical-sciences secondary-school teachers in South Africa (and, maybe, other second-language-instruction contexts) possess sufficiently clear understanding of the concepts regarding atoms and molecules and, simultaneously, to verify the extent to which they possess language-mastery levels adequate for the conceptual demands of the theme. The frequent presence of incorrect information acquired in pre-university instruction suggests the possibility of serious inadequacies in this regard. This recommends specific measures at teacher-training level to prevent further perpetuation of misconceptions. Emphasis on concepts and their expression would be fundamental to ensure that teachers are empowered to teach these concepts satisfactorily. This requires a paradigm shift to perspectives in which language becomes an integral component of science education (Sutton, 1992) and the relationships between language and concepts are clearly highlighted.

1. 5. REFERENCES

Alexander N. (Ed.), (2005). *Mother-tongue based bilingual education in South Africa: The dynamics of implementation*. Cape Town: Salty Print.

Benson, C. (2004). *The importance of mother tongue based schooling for educational quality*. 2005/ED/EFA/MRT/PI/9.

Brock-Utne, B., & Hopson, R.K. (Eds.), (2005). *Languages of instruction for African emancipation – focus on postcolonial contexts and consideration*. Cape Town: CASAS.

Brock-Utne, B., & Skattum I. (2009). *Languages and education in Africa: A comparative and transdisciplinary analysis*. Oxford: Symposium Books.

Brooks, D.T. (2006). *The role of language in learning physics*. PhD dissertation, State University of New Jersey.

Carré, C. (1981). *Language teaching and learning: Science*. London, UK: Ward Lock.

Davies, F., & Greene, T. (1984). *Reading for learning in the sciences*. Edinburgh: Oliver and

Boyd.
Fang, Z. (2006). The language demands of science reading in middle school. *International Journal of Science Education*, 28(5), 491–520.
Fleish, B. (2008). *Primary education in crisis: Why South African school children underachieve in reading and mathematics*. Cape Town: Juta & Co.
Harre, R. (1970). *The Principles of Scientific Thinking*. Chicago: Chicago University Press.
Heugh, K.A. (2009). Into the cauldron: An interplay of indigenous and globalised knowledge with strong and weak notions of literacy and language education in Ethiopia and South Africa. *Language Matters, Studies in the Languages of Africa,* 40(2), 166–189.
Love, A., & Mammino, L. (1997). Using the analysis of errors to improve students' expression in the sciences. *Zimbabwe Journal of Educational Research*, 9(1), 1–17.
Mammino, L. (2003). *Chimica viva*. Florence: D'Anna.
Mammino, L. (2003). *Chimica aperta*. Florence: D'Anna.
Mammino, L. (2005). Language-related difficulties in science learning. I. Motivations and approaches for a systematic study. *Journal of Educational Studies*, 4(1), 36–41.
Mammino, L. (2007). Language-related difficulties in science learning. III. Selection and combination of individual words. *Journal of Educational Studies,* 6(2), 199–214.
Mammino, L. (2008). Orbitals in chemistry and in chemical education. *Anuario Latinoamericano de Educación Química* XXIII, 42–46.
Mammino, L. (2010). The mother tongue as a fundamental key to the mastering of chemistry language. In C. Flener & P. Kelter (Eds.), *Chemistry as a second language: Chemical education in a globalized society* (pp. 7–42). Washington: American Chemical Society.
Mammino, L. (2011a). Importance of language mastering and mother tongue instruction in chemistry learning. Paper presented at the *8th LOITASA Workshop*, Cape Town.
Mammino, L. (2001b). Teaching chemistry in a historically disadvantaged context: Experiences, challenges, and inferences. *Journal of Chemical Education*, 88(11), 1451–1453.
Mammino L. (2012). Focused language training as a major key for bridging the gap between secondary and tertiary instruction. In D. Mogari, A. Mji & U.I. Ogbonnaya (Eds.) *ISTE International Conference Proceedings* (pp. 278–290). Pretoria: UNISA Press.
Mammino, L. (2013). Teacher-students interactions: The roles of in-class written questions. In Mei-Hung Chiu (Ed.), *Chemistry Education and Sustainability in the Global Age* (pp. 35–48). Dordrecht: Springer.
Mtshali, N. & Smillie, N. (2011). Many of our kids can't read or write: Study shows pathetic state of primary school education. *Sunday Time*, June 29.
Munby, A.H. (1976). Some implications of language in science education. *Science Education*, 60(1), 115–124.
Muralidhar, S. (1991). The role of language in science education: Some reflections from Fiji. *Research in Science Education,* 21, 253–262.
Norris, S.P., & Phillips, L.M. (2003). How literacy in its fundamental sense is central to

scientific literacy. *Science Education*, 87, 224–240.

Norris, S.P., & Phillips, L.M. (2008). Reading as inquiry. In R.A. Duschl & R.E. Grandy (Eds.), *Teaching scientific inquiry: Recommendations for research and implementation* (pp. 233–262). Rotterdam: Sense.

Qorro, M. (2011, March). Language planning and policy in Tanzania: When practice does not make perfect. Paper presented at the *8th LOITASA Workshop*, Cape Town.

Reddy V., Kaniee, A., Diedericks, G., & Winnaar, L. (2006). *Mathematics and science achievements at South African schools in TIMMS 2003*. Pretoria: HSRC Press.

Richman, R. M. (1998). In defense of quantum numbers. *Journal of Chemical Education* 75(5), 536.

Sutton, C.R. (1992). *Words, science and learning*. Buckingham: Open University Press.

Wellington, J. & Osborne, J. (2001). *Language and literacy in science education*. Buckingham & Philadelphia: Open University Press.