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Canan NAKIBOGLU
Balikesir University, Necatibey Education Faculty

INSTRUCTIONAL MISCONCEPTIONS OF TURKISH PROSPECTIVE CHEMISTRY TEACHERS ABOUT ATOMIC ORBITALS AND HYBRIDIZATION

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ABSTRACT: The research described in this paper is an investigation into the conceptions held about atomic orbitals, hybridization and related concepts by prospective chemistry teachers. The research was carried out with the participation of a total of 167 undergraduate students from two faculties of Balikesir University in Turkey. The subjects completed a diagnostic test by responding, in writing, to open-ended and multiple-choice questions about atomic orbitals and hybridization. Students' responses and explanations were analysed, and response categories were established. The results indicated that students in the field of chemistry had some misconceptions about atomic orbitals, hybridization and some other concepts related to hybridization. The atomic orbital concept is one of the most important pre-requisite concepts in learning about hybridization. The effects of understanding the atomic orbital concept in learning about hybridization were also investigated. Finally, some suggestions were made for a more effective teaching approach to ensure better learning of the topic. [*Chem. Educ. Res. Pract.*: 2003, *4*, 171-188]

KEY WORDS: *atomic orbitals; hybridization; instructional misconceptions and prospective chemistry teachers*

INTRODUCTION

The science education literature contains a large number of studies about students' understanding of scientific phenomena (Gilbert *et al*., 1982; Griffiths & Preston, 1992; Lenton & Turner, 1999; Bahar *et al*., 1999). The research on students' misconceptions has become a central issue in science education for the past two decades because they are presumed to be deeply rooted, instruction-resistant obstacles to the acquisition of scientific concepts (Lawson, 1988).

Skelly and Hall (1993) defined a misconception as a mental representation of a concept, which does not correspond to currently held scientific theory. They divided misconceptions into two categories: experiential and instructional. The experiential misconceptions are also referred to as alternative, intuitive or native conceptions. In experiential misconceptions a concept that has been understood, at least to some extent, through everyday experience and interaction with the phenomenon involved. Examples of experiential misconceptions occur in connection with phenomena such as motion, energy, and gravity. Misconceptions pertaining to some chemical phenomena, however, are fundamentally different because the existence of atoms and molecules are not directly within the realm of everyday experience. Misconceptions pertaining to these more abstract phenomena result from some instructional experience, within or outside of the classroom, including independent study (Skelly & Hall, 1993).

Herron (1996, p.187) also found it useful to divide misconceptions into two categories. 'One category deals with what happens in the physical world.' In this category students' ideas are simply contrary to empirical facts. Other misconceptions deal with students' explanations of what happens in the natural world. In most cases those explanations are logical from the students' point of view, are consistent with their understanding of the world, and are resistant to change. He suggested three generalisations because of their relationship to Piaget's description of formal operations and also cited other generalisations that could be drawn from the research on misconceptions. These three generalisations are:

1. Many misconceptions are related to concepts that involve *proportional relationships:* density, equilibrium, mole, acceleration, and rates of various kinds.
2. Many misconceptions are related to *theoretical models that require the student to interpret observations in terms of something that cannot be experienced directly:* explanations in terms of genetics and evolution, explanations in terms of an atomic model, and explanations in terms of probabilistic models.
3. Many misconceptions are related to *difficulty in following chains of logical inference (if.... then…therefore reasoning).*

One of the various sources of instructional misconceptions is prior knowledge. The learner's prior knowledge is the most important variable in the success of learning science. Some researchers report that the students' prior knowledge is restructured during lessons (Gailli *et al*., 1993; Hoz *et al*., 2001). Hoz *et al.* (2001) reported that

> "learning new subjects is either facilitated by certain specific background knowledge, or is difficult or impossible without such knowledge" (p.187).

Skelly and Hall (1993) also said that

> "If the learner's prior knowledge needed to process new information is incomplete, the knowledge gaps will result in confusion, inaccurate reasoning, and eventually in the formation of misconceptions. If the learner's prior knowledge structure contains misconceptions, these can cause further faulty reasoning and incorrect concept formation" (p.1504).

THEORETICAL FRAMEWORK

Fundamental questions of chemistry include how atoms are bonded together to form compounds and how the formulas and structures of compounds are dictated by bonding forces. One of the main goals in chemistry is to be able to predict and understand the properties of compounds on the basis of their composition and structure.

Some studies indicate that students have misconceptions and learning difficulties concerning atomic structure, chemical bonding and matter. (Cros *et al*., 1986; Cros *et al*., 1988; Taber, 1994; Tan & Treagust, 1999; Harrison & Treagust, 2000). Only a few researchers have touched upon students' difficulties and misconceptions related to the fundamental characteristics of hybridization (Zoller, 1990; Taber, 2001; Taber 2002). According to Zoller (1990) the misconceptions and misunderstandings when learning hybridization can develop among students because of the problems related to understanding the meaning of some of the prerequisite concepts. The understanding of the concept of atomic orbital, the real meaning of the s, p, d, f designations and the directions of orbitals are fundamental in learning about hybrid orbitals and hybridization. Such understanding is essential to learning other concepts, such as covalent bonding, molecules and matter. Taber (2001) suggested that having learned to think about atomic structure in terms of electron shells may impede learning about orbitals, and that learning the details of shapes and designations of atomic orbitals then acts as an impediment to thinking about molecular structure in terms of molecular orbitals. Taber (2001) reported that when learners were first taught about orbitals some seemed to take this term as a synonym for shells, and for orbits: so all three terms tended to be used interchangeably. He also said that students confused molecular orbitals with atomic orbitals: suggesting that bonding electrons in bonds in molecules were in orbitals they designated as ‘s’ or ‘p’ or confusing sets of rehybridized molecular orbitals (e.g., sp^3 hybrids) with molecular orbitals.

An obstacle related to atomic structure is that students are still using the Solar System Model or a simple nucleus/electron shell model in explaining the structure of atom. In Turkey, eleventh grade students’ misconceptions and learning difficulties about orbital concept and modern atom theory were studied (Nakiboglu & Benlikaya, 2001). The findings of this study indicated that 51% of students used the Solar System Model or a simple nucleus/electron shell model while explaining the atomic structure. Most of these students thought that orbitals were equivalent to orbits or shells. Similar findings were reported by Tsaparlis and Papaphotis (2002) for twelfth-grade Greek students who continued to think in terms of the old quantum theory and that the electrons rotate around the nucleus like the planets around the sun.

Similar difficulties can also be seen among the university students. Cros *et al*. (1988) concluded from studies conducted with second year university students that:

> “it was quite evident that they did not have a clear understanding of the interactions associated with the atomic model. Although the students had followed courses where their discussion of the Bohr atom and of the Schrödinger model had been quite extensive, their notion of the atom had changed very little” (p.333).

Zoller (1990) indicated that the roots of many difficulties and misconceptions that freshman students have are due to their deficient understandings of the complicated, abstract and non-intuitive quantum model of the atom. Tsaparlis (1997) made an analysis of undergraduate performance on a final examination in a quantum chemistry course in Greece. This analysis indicates that a number of aspects of the course seemed to cause difficulty for students, including definitions of atomic and molecular orbitals, and the approximate nature of the orbital models available in many-electron atoms. Cervellati and Perugini (1981) also reported that some first year Italian University students identified orbitals with energy levels, and others thought they were electron trajectories. In the USA, Nicoll (2001) interviewed undergraduate students and found that students used the terms “orbital” and “shell” interchangeably throughout their interview.

Robinson (1998) has suggested that the Octet Rule can also be considered as another important obstacle in perceiving the hybridization topic, just as it has been found to be when studying chemical bonding. He stated that students use the Octet Rule as a basis for explaining chemical reactions and chemical bonding rather than using it as a guide to identify stable species. Taber (1995) also suggested that the Octet Rule is a cause of a widespread epistemological learning block among chemistry students. Therefore, he recommended instructors revisit how, and in conjunction with what other knowledge, the rule is presented.

The literature reviewed above was the departure point as well as the rationale for conducting the present study delineating what and where the difficulties about hybridization are. The research question which provided a focus for the research reported in this article is:

What instructional misconceptions and learning difficulties do students acquire about atomic orbital, hybridization topic and some concepts relating to hybridization?

METHOD

Participants

Participants in the present study were drawn from two faculties of Balikesir University in Turkey: the Science and Art Faculty, which has 4 year programs, and the Education Faculty, which has pre-service teacher training programs. High school chemistry teachers come from two sources in Turkey. One is Education Faculties, the other is Science and Art Faculties. The purpose of the chemistry teacher training program is to educate teacher candidates for chemistry teaching in high schools or Lycees. If graduating students attending a chemistry major program in Science and Art Faculty would like to be high school chemistry teachers, they have to complete the pedagogic certificate courses. These two faculties follow the credit-hour system. The chemistry courses and their credit hours for each program are very similar to each other (Nakiboglu, 1999).

A total of 167 undergraduate chemistry students studying in these faculties (85 in 4th semester, 58 in 6th semester, and 24 in 8th semester) participated in the study. Subjects ranged in ages between 19-23 years. All of the participants studied General chemistry courses 1 and 2 in their first year at university. All of them also took Inorganic Chemistry course 1 in the first semester of their second year. Only 85 of the participants, who were in the 4th semester, were taking the Inorganic Chemistry course 2 while the study was being undertaken. The others had taken this course in their second semester of their second year.

The participants' past experiences about atom and hybridization: In Turkey, the atom concept is first taught to students in science lessons in the 4th grade of Elementary schools (i.e. c. age 9-10: Elementary Education covers the 8 years over the 6-14 age range). Brief explanations of atomic structure are given in the 7th grade (ages 12-13) and a general introduction to chemical bonding is made in the 8th grade (ages 13-14).

The formal chemistry courses, which go on for three years, start with secondary education, which is also called high school or Lycée. The quantum mechanical model and chemical bonding are regular parts of Turkish high school chemistry curriculum. In the 9th grade (age 14-15), after learning about Dalton's theory, components of atomic theory (e.g. Bohr model) are taught, and a general introduction to the quantum mechanical model (or Modern Atom Theory) is provided. Students meet the concept of the orbital for the first time during this instruction. They are only taught the first quantum number and orbital types (s, p, d, f), and only the shapes of s and p orbitals are presented. General explanations about the hybridization topic are first provided in the 11th grade (age 16-17).

The chemistry teachers in Turkish secondary schools usually prefer teaching with traditional techniques. They tend to concentrate on solving the problems through algorithmic approaches, rather than concept learning. It is considered that practising examples in this way is the best preparation for the university entrance examination (OSS). Additionally, the fact that the high school chemistry curriculum prescribes a lot of material to be covered is perceived as a real barrier to an emphasis on conceptual learning.

"Atomic structure" and "chemical bonding" have an important place in the general chemistry courses 1 and 2 taught in the first academic year at university. Atomic structure and related theories are generally taught in general chemistry course 1. Some instructors prefer teaching "hybridization" in general chemistry course 1 but some prefer teaching it in general chemistry course 2. Again in general chemistry courses teaching students to solve problems is more of a focus than teaching the concepts. General chemistry courses are sometimes considered to contain more physical chemistry than is appropriate for many participants (Tsaparlis & Papaphotis, 2002). This limits the time available for teaching the abstract topics and concepts such as atomic and molecular structure, and prevents those topics being learnt meaningfully.

"Quantum mechanical model" and "hybridization" are taught again in Inorganic Chemistry course 1, in detail. At the beginning of the Inorganic Chemistry course 1 taken by the participants in the study, atomic structure, Bohr Theory and Quantum mechanical model are discussed very extensively. During the discussion of the Quantum mechanical model the following concepts and topics are studied: Wave nature of the electron and the Broglie relation, Schrödinger equation and the results of its solution for hydrogen atom, atomic orbitals and quantum numbers, the radial functions of hydrogenic orbitals, the radial probability functions, angular wave functions, symmetry of orbitals, electron arrangements in poly-electronic atoms and shielding.

Before teaching "hybridization", Valence Bond Theory is taught. The instruction usually begins with the explanation of the reason why carbon atom makes 4 equivalent bonds in a methane molecule. Later different kinds of hybridization are taught and formations of these hybrid orbitals by the addition and subtraction of angular wave function are shown diagramatically. Finally the following concepts and topics are taught: energy of hybridization and determining the structures of molecules, multiple bonding, delocalization, the effect of hybridization on electronegativity.

Very few of the textbooks used by the participants in their both General Chemistry and Inorganic Chemistry courses have been written by Turkish authors (Ozcan, 1998; Tunali and Ozkar, 1993). Books commonly used in General Chemistry courses have usually been translated into Turkish (Petrucci and Harwood, 1993; Mortimer, 1989). In Inorganic Chemistry courses the instructor mostly makes use of the books *Inorganic Chemistry: Principles of structure and reactivity* (Huhey *et al.,* 1993) and *Inorganic Chemistry* (Shriver & Atkins, 1999).

Instruments

To identify misconceptions and learning difficulties about hybridization, a pilot study was conducted. A sample of 10 prospective chemistry teachers participated in this process. They were asked some questions about atomic orbital, hybridization and some other concepts relating to hybridization. After this study some test questions were designed by the author who obtained a doctorate degree in Inorganic Chemistry and has experience as a chemical educator. Prior to the development of the final items interviews with the questions were undertaken with seven students to ascertain whether the questions were satisfactory or not. The author considered it very important for the students to understand the questions. This does not necessarily mean that they knew the responses, of course, but that they understood what was being asked to them, or what they should do. This interview led the experimenter to modify some of the questions and eliminate others.

After the process of modification, two university lecturers independently reviewed the items of the diagnostic test. Based on their comments the final items of the diagnostic test were prepared.

The diagnostic test consisted of two sections. The first section of the test contained four open-ended questions. In the second section of the test there were five multiple-choice items with two, three or four choices. A copy of the diagnostic test is located in the Appendix.

Analysis and scoring

In analyzing the four open-ended questions in the first section of the diagnostic test, a concept-evaluation scheme developed in previous research was used (Abraham *et al*., 1994; Haidar, 1997). As indicated by Haidar (1997) this scheme was selected for this study because it enables the researcher to look into the data from two angles. Firstly, student's responses can be separated into different levels of understanding. Secondly, students' misconceptions can be further analysed into different patterns.

Other researchers have used different schemes comprised of three, four or five categories but the scheme used in this study is comprised of four categories listed and defined below.

Degree of understanding	Criteria for scoring
Sound understanding	Responses that include all components of the validated response
Partial understanding	Responses that include at least one of the components of the validated response, but not all the components
Misconception	Responses that include illogical or incorrect information
No understanding	Non-sense: Irrelevant or unclear responses Rewrite: Respondents repeat information in the question as if it is an answer No response: Blank

During these analyses misconception statements were identified using a coding system. As a guide, acceptable scientific explanations were written for each question after administration of the test. The ideas used by students in responding were first identified: each response might contain one or more than one group of ideas linked together. Extended lists of ideas in response to each question were organised as much as possible in mutually exclusive categories. Thus, the coding schemes were developed and the students' ideas were coded. The coding scheme for each question began with the letter A. All the question's codes were mutually exclusive as far as possible. Finally, they were considered under the four categories mentioned above. After students' responses had been categorised, frequency distributions were calculated. To ensure reliable and valid analysis, random samples of the coding were independently checked by two university instructors and 91% reliability was achieved.

Each question was scored as correct on the second section of the diagnostic test when the desired choice was selected. Both correct and incorrect choices were taken into consideration during the evaluation of these multiple-choice questions.

The correct choices assigned 1 points, incorrect choices assigned 0 points. The reliability (Gay & Airasion, 2000, p.174) was estimated as 0.50 by using the KR-20 formula when multiple-choice items were analysed (SD=1.31). Difficulty Indexes of multiple-choice items are 0.60; 0.42; 0.69; 0.78; 0.79. Discrimination indexes of items are 0.44; 0.76; 0.62; 0.40 and 0.30.

RESULTS AND DISCUSSION

Four probes were set to elicit students' responses on hybridization in different contexts in the first section of the diagnostic test. The primary goal of the first question was to analyse the patterns of students' understandings and misconceptions of the atomic orbital concept. The atomic orbital concept is one of the most important prerequisite concepts for learning about hybridization. It was hoped to find out whether there was a connection between responses to this item and of students' understanding related to hybrid orbitals and hybridization. The second and third questions focused on students' understanding and misconceptions related to hybridization and why hybridization takes place respectively. The main goal of the fourth question was to find out whether students' understanding about hybridization has any effects on their understanding of the concept of electronegativity.

The complete list of students' ideas for their first question was coded and presented below as Table 1 according to the various levels of understanding.

According to Table 1, 5% of the undergraduate students showed a sound understanding for this question. 54% of the students suggested that an "orbital describes a region of space in an atom where an electron is likely to be found" which was considered as partial understanding.

About 29% of students showed misconceptions and seven misconception statements were identified through analysis of this question, as may be seen in Table 1. When misconception statements were considered, it was identified that 20% of students still used

TABLE 1. *Summary of levels of understanding and frequencies of different types of responses to the probe "atomic orbital".*

Type of Response	No.	%
A. Sound Understanding	9	5.4
1. The behaviour of an electron in an atom is characterised by a wave function, or orbital, the square of which defines the probability of finding the electron in various regions of space.	5	3.0
2. Each allowed combination of n, l, and m corresponds to an atomic orbital where an electron is likely to be found.	4	2.4
B. Partial Understanding	90	53.9
1. An orbital describes a place where a maximum of two electrons are found.	4	2.4
2. A solution to the Schrödinger wave equation describes a region of space in an atom where an electron may be found.	2	1.2
3. An orbital is a region which is described by quantum numbers.	3	1.8
4. Orbital describes a region in an atom where an electron is likely to be found.	81	48.5
C. Misconceptions	48	28.7
1. Orbitals are trajectories arranged around the nucleus where electrons rotate.	16	9.6
2. An orbital is a fixed energy level that the electron is found on. (Bohr Model)	17	10.1
3. An orbital is a line followed by electrons in a determined order.	1	0.6
4. An orbital is a shell in which electrons are placed.	3	1.8
5. An orbital is the classification of an atom as s, p, d, f.	1	0.6
6. An orbital is a place where electrons are arranged to be in order.	5	3.0
7. An orbital is a box that is either empty or filled by electrons.	5	3.0
D. No Understanding	20	12.0
Non-sense	3	1.8
Rewrite	0	0
No response	17	10.2

the Solar System Model they brought from high school chemistry courses in order to explain the atomic structure: these students used the notions of orbitals, shells and orbits interchangeably.

The following reasons can be suggested why students use this model for explaining atomic structure. In secondary-school textbooks in Turkey the first explanation about atomic structure is presented according to the Solar System Model. This model is given as if it was an accurate explanation and its presentation is repeated in high school level textbooks. Additionally the Bohr Model of the atom and the quantum mechanical model are taught in high school chemistry courses. Both the Solar System Model and the Bohr Model of atom are relatively easy to conceptualise and concrete. So students still bring these models readily to mind even after being taught about more sophisticated models. This suggests that their misconceptions survive university teaching and may be considered robust and resilient to change. Therefore, the undergraduate students have some problems explaining the atomic orbital concept as seen in Table 1.

According to the analysis of responses given by the students, another misconception about atomic orbitals was that the students perceived each orbital as a box, as in box diagrams or orbital filling diagrams used for electron configurations of multi-electron atoms. The following two statements showed this misconception clearly:

"An orbital is a place where electrons are arranged in order."
"An orbital is a box that can be full or empty but filled by electrons."

Furthermore, one of the students answered this question drawing a box diagram and named one box as an orbital by pointing to it with an arrow (as in Figure 1).

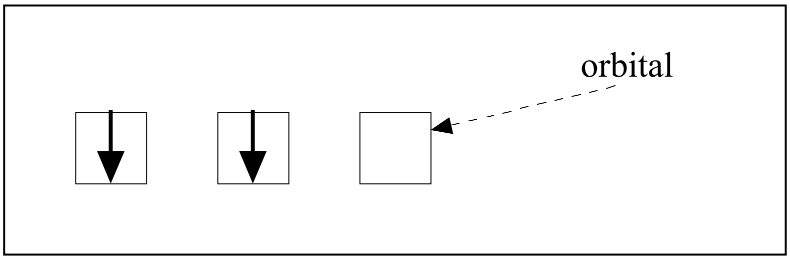

FIGURE 1: *'Box' diagram for orbitals.*

This misconception may result from the presentation of the orbital filling diagrams used for electron configurations in chemistry textbooks. A statement in such a book potentially encouraging this kind of misconception is as it is below:

> "It is convenient for many purposes to draw "box diagrams" of electron configurations in which boxes represent individual orbitals, and electrons and their spins are indicated by arrows" (Huheey, 1978, p.31)

Even the warning below has been made in this textbook giving rise to the suspicion that the author was aware of the potential for a misunderstanding:

> "Such devices can be very useful for bookkeeping, providing pigeonholes in which to place electrons. However, the reader is warned that they can be misleading
> if improperly used" (Huheey, 1978, p.31)

In another textbook (McMurry & Fay, 1998, p.185) there is a similar statement that "An orbital-filling diagram indicates the electrons in each orbital as arrows". This misconception could be accepted as evidence that students can solve problems by algorithm without understanding the real meaning of the concept. As Tsaparlis and Papaphotis (2002) have expressed, chemistry teachers may place great emphasis on equipping students through extensive practise with chemical skills such as numerical problem solving, the placing of electrons in shells or atomic orbitals, the balancing of chemical equations - and although many teachers seem to agree that such mastery is equivalent to conceptual understanding of chemistry, many studies have demonstrated that this is not so. Tsaparlis and Papaphotis (2002) have also found out that the situation is the same with regard to the atomic and molecular structure. They say: "the ability, for instance, of students to write down electron configurations for atoms does not guarantee conceptual understanding of the underlying concepts" (p.138).

The complete list of students' ideas for second question of the first section of the test was coded and is presented below as Table 2 according to the various levels of understanding. According to Table 2 the percentage of sound understanding of the students' responses was very low (7%). For this question the level of partial understanding was higher than the level of sound understanding, but this percentage (14%) was still low.

About 51% of students showed misconceptions and 17 misconception statements about the understanding of the hybridization concept were identified through analysis of this question as seen in Table 2. One of the most common misconceptions was that the idea of hybridization of atoms obeyed the Octet Rule. Basically, this misconception can probably be attributed to the over-generalisation of the Octet Rule by students. Students think:

> "Atoms undergo hybridization because these atoms need electrons to satisfy the Octet Rule".
> "Hybridization is a process of an atom or molecule to complete the number of their valence electrons to eight".

This result quite resembles the ones that Taber (1995) obtained in his studies on the Octet Rule. One outcome of his study was that students were found to commonly use the Octet Rule as the basis of a principle to explain chemical reactions and chemical bonding: 'the full shells explanatory principle' (Taber, 1998).

The most predominant misconception was the idea that electrons play the main role in hybridization. This misconception was held by 33% of the students. 3% of the students even suggested that hybridization was the overlapping of valence electrons. Besides this, seven students thought that it was a kind of electron sharing process. The rest of the students in this group were observed to believe there was a relationship between hybridization and electron passing among orbits or shells.

In another identified misconception students perceived that hybridization was an event in which orbitals transformed to an energetically equivalent state (almost 6%). This misconception came from the students' misunderstanding of the formation of the energetically equivalent hybrid orbitals during the hybridization.

About 28% of the students showed no understanding. Some of the students in this category gave no answer to this question and the answers of others were judged to be non-sense.

The complete list of students' ideas for the third question was coded and presented below as Table 3 according to the various levels of understanding. Only 8% of the undergraduate students showed sound understanding for this question as it is seen in Table 3.

TABLE 2. *Summary of levels of understanding and frequencies of different types of response to "hybridization" probe.*

Type of Response	No.	%
A. Sound Understanding	12	7.2
1. Hybridization consists of mixing the atomic orbitals of an atom in such a way as to form new hybrid orbitals.	2	1.2
2. Hybridization is a process in which two atomic orbitals having different energy levels form new energetically equivalent hybrid orbitals.	10	6.0
B. Partial Understanding	24	14.4
1. Hybridization is the formation of new orbitals after atomic orbitals lose their s and p characters.	3	1.8
2. Hybridization is the formation of energetically equivalent hybrid orbitals by hybridization of atomic orbitals.	9	5.4
3. Hybridization is the reorganisation of atomic orbitals in which valence electrons of atoms exist.	2	1.2
4. Hybridization is the process of mixing different types of orbitals to form a new set of orbitals.	8	4.8
5. Hybridization increases the bond order of an atom in order to form a molecule.	2	1.2
C. Misconceptions	85	50.9
1. Atoms undergo hybridization because these atoms need electrons to satisfy the octet rule.	4	2.4
2. Hybridization is a process undergone by an atom or molecule to complete their valence electrons to eight.	1	0.6
3. Hybridization is promotion of electrons placed in the lowest energy level to an unoccupied orbital in the higher energy level.	4	2.4
4. Hybridization is a process in which electrons change their orbits.	7	4.2
5. Hybridization is a process in which electrons are transferred from an orbital to another one.	17	10.2
6. Hybridization is a process in which electrons in an orbital at the ground state are transferred to the excited state.	4	2.4
7. Hybridization is called the bond formation process of electrons via formation of hybrid orbitals with equivalent energy levels.	4	2.4
8. Hybridization is an equalisation process of electrons' own energies.	3	1.8
9. Hybridization is the transformation of orbitals into energetically equivalent ones.	10	6.0
10. Hybridization is the overlapping of valence electrons.	5	3.0
11. Hybridization is the distribution of electrons to the orbitals equally.	11	6.5
12. Hybridization is combining bonds by coming closer to each other.	2	1.2
13. Hybridization is a type of electron pairing.	7	4.2
14. Hybridization is distribution of electrons to orbitals equally.	1	0.6
15. Hybridization is passing of orbitals from ground state to the excited states.	1	0.6
16 Hybridization is formation of new orbitals by influencing electrons with orbitals.	3	1.8
17. Hybridization is the process of mixing electrons in a shell by transferring them to a shell in the lower lever.	1	0.6
D. No Understanding	46	27.5
Non-sense	22	13.2
Rewrite	3	1.8
No response	21	12.5

These answers showed that the students had realised that hybridization takes place to allow a proper overlap with other atoms' orbitals during covalent bonding, but they did not mention the relation between the type of hybridization and the observed geometry of the molecules. 3% of the students answered this question as either to form bonds or to increase the bond order. These answers were classed as partial understanding.

TABLE 3. *Summary of levels of understanding and frequencies of different types of response to probe "why does hybridization take place?".*

Type of Response	No.	%
A. Sound Understanding	13	7.8
1. Atoms need half-filled orbitals in order to form bonds. Some atoms need hybridization since they don't have enough half-filled orbitals necessary for bond formation.	5	3.0
2. To organise bond formation of atoms and the geometry of the molecules these atoms will undergo hybridization.	7	4.2
3. To form proper orbitals necessary for bond formation.	1	0.6
B. Partial Understanding	55	32.9
1. To form bonds.	35	20.9
2. To increase bond number.	20	12.0
C. Misconceptions	60	35.9
1. To have a more stable structure.	40	23.9
2. To form a compound in different structures.	4	2.4
3. To obey the Octet Rule.	4	2.4
4. To complete the number of the valence electrons to eight in their last orbits.	2	1.2
5. Because of an interaction and repulsion between atoms.	2	1.2
6. To make it possible to use electrons completely.	1	0.6
7. s and p orbitals are in the same energy level. When p is unoccupied, s can not be occupied, so atoms become hybridised.	1	0.6
8. To pass into excited states.	1	0.6
9. To have a proper energy level.	2	1.2
10. To decrease the energy difference among the orbitals.	1	0.6
11. It is an event coming from the characteristics of carbon atom.	1	0.6
12. Because of unoccupied orbitals atoms would like to take electrons.	1	0.6
D. No Understanding	39	23.4
Non-sense	13	7.8
Rewrite	0	0
No response	26	15.6

About 36% of students showed misunderstandings and 12 misconception statements were found. In this question the most conspicuous misconception is that hybridization takes place in order to become more stable. As Taber (2001) cited in his studies, some chemistry students explain most questions directed to them with the tendency of systems to become more stable.

This is also another misconception deriving from a tendency for hybridization to mostly be explained in the textbooks with the example of the carbon atom. When the chemistry textbooks were scrutinised, it could be seen that some of them presented hybridization of the carbon atom just after the title of hybridization while others presented the same subject after giving just a few sentences (McMurrey & Fay, 1998; Clayden *et al*., 2001; Dauglas *et al.,* 1994; Huheey *et al.,* 1993). The same thing continues during instruction and some teachers prefer teaching hybridization starting with the hybridization of the carbon atom. This situation may cause the students to think that hybridization is a property belonging only to the carbon atom.

The complete list of students' ideas for the fourth question was coded and presented below as Table 4 according to the various levels of understanding.

TABLE 4. *Summary of levels of understanding and frequencies of different types of response to probe "effects of the hybridization on electronegativity?".*

Type of Response	**No.**	**%**
A. Sound Understanding	18	10.8
1. Yes, it does. As the s character of the hybrid orbital belonging to the atom undergo hybridization gets increased, the electronegativity of this atom gets increased.	11	6.6
2. Yes, it does. The electronegativity changes depending on the s character.	7	4.2
B. Partial Understanding	3	1.8
1. Yes, it does. s orbitals have more electrons.	1	0.6
2. Yes, it does. The hybridization type of an atom taking place in a molecule changes electronegativity of that atom.	2	1.2
C. Misconceptions	22	13.2
1. Yes, it does. Electronegativity of hybridised atoms increases.	11	6.6
2. Atoms undergo hybridization according to their electronegativities.	1	0.6
3. The higher the electronegativity is, the more the atoms attract each other during hybridization.	2	1.2
4. The more the electronegativity is, the more difficult it is to excite the electrons	1	0.6
5. Since electronegativity affects the stability, hybridization has an influence on electronegativity.	1	0.6
6. Hybridization is better in atoms with a high electronegativity.	1	0.6
7. When electrons change their places, electronegativity also changes.	1	0.6
8. As the electron arrangement changes with hybridization, electron exchange is affected also.	1	0.6
9. The effects of the hybridization on electronegativity changes according to the type of atoms that form bonds.	1	0.6
10. Other electrons not forming bonding affect the electronegativity of the molecule.	1	0.6
11. Electronegativity decreases since electrons occupy the orbitals in hybridization.	1	0.6
D. No Understanding	124	74.2
Non-sense	41	24.5
Rewrite	3	1.8
No response	80	47.9

Almost 11% of the students showed sound understanding for this question. These students expressed the belief that hybridization affected the electronegativity of an atom and that the electronegativity increased as the s character of hybrid orbital increased. Misconceptions concerning the fourth question were held by 13% of students, whereas most responses indicated no understanding (almost 75%). The most common misconception was that hybridization had no effect on electronegativity but electronegativity had an effect on hybridization. This misconception was held by 7% of the students. Two statements pointing out this misconception are as follows:

> "Atoms undergo hybridization according to their electronegativities."
> "Hybridization is better in atoms with a high electronegativity."

While in fact hybridization affects electronegativity, students think just the opposite. This way of thinking gives rise to another type of misconception, as seen in misconception statements numbered 4, 7, 8 and 11. Still another misconception is about becoming more stable.

TABLE 5. *Percentage of chemistry students selecting the desired content and incorrect choice.*

		Students' responses				
Question	Correct Answer	A n (%)	B n (%)	C n (%)	D n (%)	No answer n (%)
1	A	*105 (63)*	9 (6)	19 (11)	19 (11)	15(9)
2	C	93 (56)	5 (3)	*45 (27)*	17 (10)	7(4)
3	B	43 (26)	*112 (67)*	_	_	7(12)
4	C	11 (7)	4 (2)	*147 (88)*	4 (2)	1(1)
5	A	*139(83)*	4(2)	12 (8)	4 (2)	8 (5)

The primary goal of the second section was to find out the students' understanding and misconceptions related to other concepts within the hybridization topic. Table 5 shows the desired content choice and incorrect content selected by undergraduate students in an item.

When Table 5 is examined it can be seen that 63% of the students understood the relation between hybridization and formation of multiple bonds but only 27% of them knew that sigma (σ) and pi (π) bonds are a type of covalent bonding; that 56% of them thought these two bonds were a different kind of bonding; and 10% of them thought that these two types of bond were only intermolecular forces. It may be concluded from this that many students were not aware of the importance of hybridization in the formation of covalent bonds.

Another important misconception statement obtained from analysing the multiple-choice questions is that the students think there is a relation between hybridization and ionic bonding (26%).

It can also be seen that 88% of students knew the relation between the number of hybridised atomic orbitals and the number of hybrid orbitals after hybridization. The total number of hybrid orbitals after hybridization can be easily calculated with simple mathematical operations. For this reason, students could answer this question in such a high rate. 83% of students could see the connection between hybridization and molecular geometry.

When the students' performances in the two types questions used in the first and second parts of the diagnostic test are compared, it can be seen that students are generally more successful in the second part in which the multiple choice questions have been used. Although it is usually said that chance contributes to success in the tests with multiple choice questions, it can also be said that there is a relation between the success and the features of the questions. The achievement is seen to be higher in the first question, in which the relation between the hybridization and double and triple bonds is tested, and in the fifth question, in which understanding the role of the hybridization in determining the geometric structure of the molecules is probed. When these two questions are considered, it can be realised that both of them are not especially abstract and can be relatively easily conceptualised. On the other hand, the open-ended questions, for example the ones about atomic orbitals and hybridization, are more abstract and they require the students to have learned the course material meaningfully. The fourth question among the multiple choice items is an algorithmic one. Several researchers have indicated that students are more successful in solving the algorithmic problems than conceptual problems (Nurrenbern and Pickering, 1987; Nakhleh and Mitchell, 1993). On the other hand, it can be seen that students do not have a high performance in the multiple choice questions about the sigma and pi bonds, because in this question students are required to recall their knowledge.

IMPLICATIONS FOR INSTRUCTION

The results of this study indicate that students at each level have some important misconceptions about hybridization. One of two obstacles to effective learning is that hybridization and other concepts related to it are abstract and non-intuitive. The other is that students still have problems with quite important pre-requisite knowledge in learning hybridization. It has also been observed that in the diagnostic test students were more successful at algorithmic questions than conceptual ones.

In the light of the foregoing results the following educational practices are suggested:

1. Instructional strategy should focus on; first, what is known or unknown about hybridization and then the new knowledge should be constructed upon existing knowledge. Some misconceptions are generated during the course as a product of the interaction between the students' pre-existing knowledge and teacher-initiated instruction. When teaching hybridization topics, the instructor has to be sure that students learn correctly: a) difference between orbits, orbitals and shells and that they shouldn't use them interchangeably; b) the atomic orbital concept and modern atom theory (the shape of orbitals, the number of orbitals, the direction of orbitals, the energy of orbitals); and c) Hund's Rule.
2. While teaching electron configurations of multi-electron atoms, it should be emphasised that these boxes are used in order to show the placement of electrons in orbitals as a device to aid conceptualisation and explanation. Just before starting the instruction of hybridization, it should be checked whether students have misconceptions about the meaning of these box diagrams. In addition, the instructor should make sure that they know how to write electron configurations of multi electron atoms correctly.
3. During the instruction; after reviewing the pre-existing knowledge, the importance of the hybridization process should be emphasised by explaining why atoms undergo hybridization; what the source of the driving force resulting in hybridization is; and, especially, the relation between the hybridization type of the central atom and molecular geometry. In this relation the role of hybridization must be kept in perspective. It cannot be used to predict molecular shapes; it is a way of creating localised orbitals that produce the observed shapes of molecules (Clayden *et al.,* 2001, p.105).
4. While teaching the Octet Rule to the students for the first time, the instructor should explain it in conjunction with other knowledge and call their attention to the point that this rule is not able to explain all phenomena. The instructor should express the limitations of the Octet Rule especially and give examples about the exceptions such as: compounds of noble gases (XeF_6); electron deficient species (BF_3) and compounds with expanded octets (PCl_5). Taber (1995, p.9 and 1998) also suggested that knowledge of the Octet Rule may interfere with subsequent study of other more sophisticated chemical ideas. He indicated that the Octet Rule is a useful heuristic for distinguishing atomic structures that are likely to be stable; but it is sometimes presented as if it is an explanatory principle and learners may therefore come to understand the Octet Rule as explaining chemical processes.
5. During teaching, the difference between ground state and hybrid atomic orbitals, the shape of hybrid orbital sets and their orientation should be emphasised in detail. Energy diagrams showing the energy differential between the hybrid and ground state atomic orbitals should be used. Thus, understanding of the energetics of hybridization can help students to determine the electronic structure of molecules. A similar suggestion to hinder the development of misconceptions about hybridization was made by Zoller (1990) - i.e. the showing of atomic and hybrid orbitals on an energy diagram graphically.

6. The relation between hybridization and formation of covalent bonds should be stated, and how hybrid orbitals of an atom can overlap during the formation of covalent bonds should be explained with examples. The relation between multiple bond formation and covalent bonding, and the effect of hybridization on overlap and bond properties should be emphasised. Attention to the fact that sigma and pi bonds are types of covalent bond should be emphasised.
7. Hybridization is commonly taught using first the example of hybridization of the C atom. It should be indicated that hybridization is not only a property belonging to C atoms by giving examples of hybridization of different atoms.
8. Students sometimes may use the expression "become stable" as a habitual response without knowing its real meaning, and they think it only has to be related to the Octet Rule. A similar situation is seen in the explanation of hybridization and since students relate hybridization to the Octet Rule, they think atoms undergo hybridization to form a more stable molecule. While teaching certain phenomena like hybridization in chemistry we should be very careful in using an explanation like "become stable" and if we are to use this phrase, then we should refer to the other explanations supporting it. For example, while explaining the geometry of any molecule, such as why the geometry of methane molecule is tetrahedral, it is necessary to avoid to use this expression: "Because the molecule becomes stable in this geometry". Instead, expressions explaining the situation like "the methane molecule is tetrahedral because the energy of the molecule is lowest in that configuration" should be used.

Prospects for further work

The results reported here constitute my first report of a study relating to the diagnosing misconception about hybridization. Based on these results, a qualitative study about undergraduate chemistry students' understanding of hybridization has been planned using interviews to investigate in-depth the possible reasons for misconceptions about hybridization.

CORRESPONDENCE: *Canan NAKIBOGLU, Balikesir University, Necatibey Education Faculty, 10100 Balikesir, Turkey; fax.: 0 266 2495005; e-mail: canan@balikesir.edu.tr*

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APPENDIX: DIAGNOSTIC TEST

Section 1

1. What is an atomic orbital? Explain briefly.
2. What is the hybridization? Explain briefly.
3. Why do the atomic orbitals undergo hybridization?
4. Does the hybridization have any effects on electronegativity?

Section 2

1. Are there any relations between the hybridization and double and triple bonds?
    a) Yes, there are
    b) No there aren't
    c) Partly
    d) It depends on the kind of the bond.
2. Are σ and π different kind of bonds?
    a) Yes, they are certainly different kind of bonds.
    b) No, they are a kind of ionic bond
    c) No, they are a kind of covalent bond
    d) They are only intermolecular forces.
3. Are there any relations between ionic bond and hybridization?
    a) Yes, ionic bonds are formed by hybridization of atomic orbitals
    b) No, there aren't any relation between them.
4. How many orbitals have been combined to the hybridization of sp^3 ?
    a) 1 b) 3 c) 4 d) 5
5. Does hybridization determine the geometric structure of the molecules?
    a) Yes, it does
    b) No, it doesn't
    c) Sometimes it does
    d) There are no relations between hybridization and molecular geometry.

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