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ORIGINAL ARTICLE

Studying Students' Representations of the "Orbital" and "Electron Cloud" Concepts

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Abstract

The study investigates secondary students' understanding of "orbital" and "electron cloud" concepts in different quantum contexts (for values of the ʿprincipal quantum number n = 1 and n = 2) on the basis of their verbal and pictorial representations, evaluating also their consistency. Participants, which were 192 12th-grade students from six urban secondary schools of Northern Greece, represented these two concepts through two corresponding tasks of a paper-and-pencil assessment tool, each of which comprised two parts for verbal and pictorial representations, respectively. Results provide evidence that although students struggle to express verbally the orbital and electron cloud concepts, their competences in the corresponding pictorial representations are relatively better, exhibiting inconsistencies between verbal and pictorial representations. Inconsistencies also exist between representations of the orbital and electron cloud concepts, since students appear to have verbally a better understanding of the electron cloud than the orbital, whereas the opposite holds true for their pictorial representations. Comparing verbal and pictorial representations, the pictorial ones appear to be more consistent tools, whereas a quantum context defined by n = 2 seems to be more challenging for students compared to that of n = 1. Furthermore, an analysis of student profiles leads to their categorization in four classes, providing additional relevant information. Implications for science education are also discussed.

KEY WORDS: Electron cloud; orbital; students' representations

INTRODUCTION

Students' understanding of quantum concepts related to the atomic structure is one of the most highly interesting research fields of science education (e.g., Allred and Bretz, 2019; Dangur et al., 2014; Cascarosa Salillas et al., 2022; Derman et al., 2019; Nakiboglu, 2003; Özcan, 2013; Papaphotis and Tsaparlis, 2008; Stefani and Tsaparlis, 2009; Sunyono et al., 2016; Zarkadis et al., 2021, 2022). Among such quantum concepts, "orbital" and "electron cloud" seem to be significantly problematic for the students, mainly due to many understanding preconditions, like the "probability density" in the case of the electron cloud, or the lack of physical meaning, as it holds true in the case of orbital. Relevant studies focus more often on students of upper secondary and tertiary education since the teaching of such concepts in lower secondary education is not always systematic across the various educational curricula all over the world. In Greece for instance, only secondary students of the 12th grade (age 18), who followed the direction of "science and mathematics" (one of the three available), are taught the quantum model and related concepts for three 1-h lessons per week (Greek Pedagogical Institute, 2003). The corresponding teaching includes verbal descriptions of the atomic orbital and the electron cloud, together with those of the density probability, the uncertainty principle, the wave function, and the quantum numbers. These verbal descriptions are also companied by pictorial representations of the hydrogenic atomic structure types.

However, the way in which students connect these two kinds of representation (verbal and pictorial) is a subject under discussion, and there are many cases where relevant inconsistencies have been found (e.g. Dangur et al., 2014; Zarkadis et al. 2021, 2022). Thus, an effort to investigate students' understanding of these quantum concepts prerequisites the availability of evidence from both kinds of representation, the coevaluation of which could provide us with a more realistic view of what students have ultimately crystallized in their mind. Besides, relevant inconsistencies are always expected to a certain degree, since verbal and pictorial representations appear to have complementary functions (Ehrlén, 2009).

As a result, in the present study, both verbal and pictorial students' representations are taken into account to investigate their understanding of "orbital" and "electron cloud" concepts. Furthermore, since these two concepts are taught in the general quantum context, the effect of different quantum contexts, such as those created by different values of the first quantum number, are also studied. In addition, the question concerning the overall student profiles that are configured when taking into account all the above is sought to be answered.

THEORETICAL FRAMEWORK

Students' Representations of the Orbital Concept

Although there were attempts to investigate the understanding of the "orbital" in younger ages (e.g., Cokelez, 2012), a quite sufficient view of students' difficulties in relation to such a concept can be found in studies launched for students around 16–18 years old (at the upper secondary level) and older ages (at the undergraduate level). At these studies, students' difficulties seem to originate mainly from an inability to conceptualize the probabilistic nature of the quantum concepts in general, and a student's trend to always seek for a physical meaning for every concept. Even students, who appear to have a probabilistic view of the concept of orbital to a certain degree, seem to hardly differentiate it from other relevant concepts like that of the electron cloud (e.g. Allred and Bretz, 2019; Stefani and Tsaparlis, 2009; Stevens et al., 2010).

Starting from the lack of understanding of the probabilistic model for the submicroscopic world or its limited comprehension, many students' misunderstandings and confusions can be identified. One of the most characteristic relevant findings concerns the confusion existing among the concepts "orbital," "orbit" and "shell" (Allred and Bretz, 2019; Akaygun, 2016; Taber, 2002a; Tsaparlis and Papaphotis, 2002, 2009). In these cases, students' verbal and pictorial representations indicate the existence of a strong influence by the deterministic/mechanistic context, and their approaches proceed through an analogous reasoning (Nakiboglu, 2003; Nicoll, 2001). As a result, the concepts are often used interchangeably by the students, whereas quite often, their representations indicate conflating characteristics coming from both probabilistic and deterministic contexts, combining orbital shapes with orbiting electrons (Park and Light, 2009). Thus, for instance, orbitals can be identified as paths that electrons follow as they move around the nucleus (Muniz et al., 2018), or electrons are presented to move on orbitals as differently-shaped orbits (Kiray, 2016).

Looking through another aspect of the deterministic model, students try quite often to attribute a physical meaning to the orbital concept, considering it as a definite well-bound space (Tsaparlis and Papaphotis 2002, 2009). Even at the undergraduate level, the atomic orbital is considered to be a region in space, whether the concept of probability of finding an electron is included or not (Stefani and Tsaparlis, 2009). It is characteristic the case of 1st-year university students, reported by Papaphotis and Tsaparlis (2008), where they cannot accept the possibility of the hydrogen atom's electron in the ground state being outside the space defined as 1s orbital unless it is stimulated.

As for the students, who appear to have developed the concept of orbital through a probabilistic context, to a certain degree, a number of difficulties still remain. Thus, there is a difficulty in providing a satisfying interpretation of the atomic and molecular orbitals (Nakiboglu, 2003; Tsaparlis, 1997; Tsaparlis and Papaphotis 2002), whereas a difficulty in differentiating these two concepts is also apparent (Taber, 2002b, 2005). In addition, according to Ochterski (2014), students seem to evaluate the size of an orbital based on the number of electrons they contain. For instance, they consider 2s and 3s having the same size, since both orbitals contain the same number of electrons.

In any case, independently to the degree, in which students have developed (or not) the probabilistic model, confusion between the use of concepts "orbital" and "electron cloud" appears to be quite often present (Stevens et al., 2010). Thus, even at the undergraduate level, the atomic orbital is often considered as probability, orbitals are presented as clouds of specific shape (Stefani and Tsaparlis, 2009), whereas the orbital concept appears to be synonymous to the electron cloud since it is described like a "region" where electrons are most possible to be found or where the electrons move (Allred and Bretz, 2019). Expectably, similar problems in differentiating orbitals, electron cloud, or/and electron probability have been found in secondary students (Taber, 2002a,b; Stefani and Tsaparlis, 2009).

Students' Representations of the Electron Cloud Concept

In the case of electron cloud, the attribution of a physical meaning by the students seems to be easier compared to the concept of orbital, probably due to an influence by the clouds in the sky (Kiray, 2016). Thus, relevant studies implemented even in lower secondary education showed a preference of students for the "electron cloud model" when they were asked to depict the atom (Cokelez, 2012). However, the main students' difficulties emerge again at the upper secondary education and the university level as well. Similarly to the orbital concept, any understanding of the electron cloud concept prerequisites the acceptance and the conceptualization of the probabilistic nature of the quantum concepts related to the atomic structure. Besides, as it is reported above, these two concepts (i.e., orbital and electron cloud) are not clearly differentiated in students' minds and many understanding problems appear to be common. However, in the case of the electron cloud, students' difficulties are rather connected to the nature of the electron and its position and probability to be found in the "orbital region."

Starting here from students' ideas for the relation of the electron cloud with the electron nature, a common finding from secondary to tertiary education is that electron clouds contain electrons (e.g., Ireson, 2000; Zarkadis et al., 2017). It is characteristic the evidence provided by Harrison and Treagust (1996), that 50% of the student sample perceived the electron cloud concept as a "structure in which electrons were embedded" and thus, the electron cloud was viewed as a "separate entity" in which electrons are contained. At an undergraduate level, students sometimes consider electrons wave behavior to be a cloud of smeared charge, using both characteristics of the Schrödinger and the Bohr models (Müller and Wiesner, 2002), whereas often they describe electron clouds having macroscopic properties that allow us to see electron clouds, relevant shaded areas and shapes-electron clouds with an electron microscope or suitable instruments (Stefani and Tsaparlis, 2009). According to Kiray (2016), many students believe that an electron cloud is formed by a large number of electrons which rotate around the nucleus (an "electronium model") or electrons act like waves moving in certain orbits creating a cloud-like form (a "wave orbit model). Furthermore, in cases where students are provided with pictorial representations of the atom, they often interpret dots in an "Electron probability representation" (Allred and Bretz, 2019), as "places where the electron could be," as the location of electrons over time, as multiple particles, or as sub-particles. In addition, when the "Boundary surface representation" of the atom is presented to students, some of them interpret the surface as a uniform probability of finding electrons in the atom, while some others consider that the uniform color and the defined shape of the representation indicate the equal probability of electrons to be anywhere in the atom (Allred and Bretz, 2019).

Consequently, confusion appears to be present as for the relation between the concept of electron cloud and those of orbit, orbital, and shell. Harrison and Treagust (2000) found that students of Grade 11 have difficulties in differentiating the concepts "electron shell" and "electron cloud," whereas Zarkadis et al. (2017) reported that 12th grade students consider electron clouds moving in shells. Similarly, in 1st-year university students' pictorial representations, the picture of the electron cloud is perceived as an orbiting electron cloud or a flattened/spread out orbit (Papaphotis and Tsaparlis, 2008), or as a small electron cloud/packet moving on specific orbits (Tsaparlis and Papaphotis, 2009). Characteristic is also the "probability orbit model" suggested by Kiray (2016), where each point of an orbit represents a different electron, and thus, electrons as particles move in a nebulous structure around the nucleus. As Stevens et al. (2010) reported as well, there is a wide range of ages/grades, where students used the term electron cloud to describe the distribution of electrons relied on orbitals, and very often orbitals are labeled as electron clouds. Thus, taking also into account research evidence like this reported at the end of the previous section, it is quite obvious that electron cloud and orbital are concepts not clearly differentiated by the students.

RATIONALE OF THE STUDY AND RESEARCH QUESTIONS

Since students' understanding of quantum concepts related to the atomic structure is of great importance for science education, we have launched a research project moving in such a research context. Thus, the present study is a part of a wider project targeting students' conceptualization of specific quantum concepts and their verbal and pictorial representations, having already provided us with evidence recently published (Zarkadis et al., 2021, 2022). Focusing on the concepts of orbital and electron cloud this time, we take advantage of the complementary nature of the verbal and pictorial representations (Ehrlén, 2009) and we seek a more realistic view of student representations of these two fundamental concepts and their differentiations. To do so, a coevaluation of these two kinds of representation is carried out through robust data analysis techniques using as covariates additional factors dealing with the consistency of students' representations, such as those created by different values of the first quantum number (Zarkadis et al., 2017). Thus, a systematic analysis of data taking place in such a context could provide us with more reliable answers to the following research questions:

1. How do students represent the "orbital" and "electron cloud" concepts?
2. To what extent factors such as the kind of representation (verbal or pictorial), the concept itself (orbital or electron cloud), and the quantum context (the value of the principal quantum number n = 1 or n = 2) are related to the consistency of students' relevant representations?
3. Are there particular student profiles emerged in relation to their representations?

METHODOLOGY

Sample and Procedure

The research took place in Northern Greece involving 192 high school students of the 12th grade (105 male and 87 female) from six urban public schools. Participants came from diverse socioeconomic backgrounds and were enrolled in mixed-ability classes, adhering to the National Science Curriculum for Greece as outlined by the Greek Pedagogical Institute (2003), whereas they were following the "science and mathematics" curriculum using the same textbook. Students took part in the research anonymously and voluntarily, fully informed about the study's objectives, with the assurance that their performance in the study would not be associated with their academic records.

Instrument

The examination of students' representations of the "orbital" and "electron cloud" concepts was taken place verbally and pictorially through two tasks, which were part of a paper-and-pencil assessment tool aiming to investigate students' conceptualization of specific quantum concepts. The first task examined the "orbital" and the second the "electron cloud," respectively, whereas both tasks comprised two parts, as follows:

- In the first part, an open-ended question, students were asked to verbally describe the "orbital" and the "electron cloud" concept, in Tasks 1 and 2, respectively.
- In the second part, students were asked to draw pictorial representations of all orbitals (task 1) or electron clouds (task 2), respectively, for two specific values of the "principal quantum number" (in particular n = 1 and n = 2), naming any component they draw and explaining any differences between these two cases of different values.

Data were collected during the second semester of the school year; approximately 2 months after students have been formally taught quantum concepts such as quantum numbers, orbital, and electron cloud, including their representations. The time available for the completion of both tasks was 25 min. To detect and correct possible problems, the instrument underwent testing during a pilot study involving 74 participants before implementation in the main study. No modifications were made to the final instrument.

As for the content validity of the assessment tool, this was established by the two first authors (as subject experts), to ensure that the tool measures what it is expected to be measured in line with the corresponding textbook. According to the latter, atomic orbitals are electron's wave functions with no physical meaning, derived as solutions of the Schrödinger equation and expressed in the form of $\psi(x,y,z)$, where x,y,z are the coordinates specifying the position of the electron around the nucleus ($\psi = 0$ denotes the absence of the electron and $\psi \neq 0$ its presence). On the contrary, ψ^2 is reported as the density of the electron cloud, having great physical importance since it expresses the probability of the electron being found in a certain position around the nucleus. As for the relation between quantum numbers and the "orbital" and "electron cloud" concepts, the corresponding textbook reports that the values of the quantum numbers n, l, and m_l correspond to particular solutions of the Schrödinger equation defining a particular orbital of the atom, since they specify size, shape, and orientation of the orbital, respectively. On the contrary, the quantum number of spin (m_s) does not contribute to the specification of the atomic orbital.

Evaluation of students' responses to the tasks entailed assessing their correctness and completeness, while also considering the scientific perspective articulated in the corresponding student textbook for both "orbital" and "electron cloud" concepts. Consequently, responses to the first part of each task were coded and categorized by the first and second authors (categories SA to NU) based on the criteria outlined in Table 1.

Initially, the Cohen's kappa coefficient yielded a value of 0.85, whereas any discrepancies between the two raters were resolved through discussion to the complete agreement. The Cronbach's alpha coefficient indicated acceptable overall internal consistency reliability, with a value of 0.78.

For the evaluation of students' responses to the second part of each task, criteria from relevant studies (Akaygun, 2016; Tang et al., 2019; Zarkadis et al., 2021, 2022) were applied. This evaluation took into consideration characteristics of pictorial representations, including size, shape, orientation of orbitals (task 1) or electron clouds (task 2), as well as their spatial arrangement in a three-dimensional system of x, y, z axes (e.g., relative size, position, alignment, or scale). Consequently, students' pictorial representations were categorized in the following levels:

- Level A3: Representations with *quantum characteristics* correct and complete[1] as for the size, shape, and orientation of the orbitals or electron clouds.
- Level A2: Representations with *quantum characteristics* correct but incomplete as for the size, shape, and orientation of the orbitals or electron clouds.
- Level A1: Representations with *quantum characteristics* incorrect (complete or not) as for the size, shape, or orientation of some orbitals or electron clouds. Furthermore, when orbitals are depicted instead of electron clouds.
- Level B: Representations with *hybrid characteristics* correct or incorrect (complete or not). When orbitals or electron clouds were depicted with naïve and quantum characteristics mixed.
- Level C: Representations with *naïve characteristics* correct or incorrect (complete or not). When orbitals or electron clouds were depicted as dots, orbits, shells, or region of space without reference to probability or probability density.
- Level D: Unclear representations or no response.

For this second part, Cohen's kappa value was initially found 0.82, and any discrepancies between the two raters were also discussed to ultimately reach an agreement. The Cronbach's alpha value for pictorial representations was found acceptable 0.76. Some characteristics examples of students' pictorial representations are presented in Figure 1.

Data Analysis

To assess the consistency between pictorial representations for each task, an examination of the symmetry of the corresponding contingency sub-tables was carried out. The symmetry evaluation was performed using the McNemar-Bowker test. In cases where the assumptions of the McNemar-Bowker test were not met, a Monte Carlo multinomial exact test with 1000 trials was employed as an alternative. Furthermore, *post hoc* McNemar tests with Bonferroni-adjusted alpha levels were conducted to identify any statistically significant transitions using two tests from the R package "r companion" (Mangiafico, 2017), the "mcnemar test" and the "nominal symmetry test."

To identify clusters of students characterized by similar profiles regarding their knowledge and competence in representing atomic structures, latent class analysis (LCA) was conducted using Latent Gold version 5.1 (Vermunt and Magidson, 2016), through a procedure described in details in Zarkadis et al. (2022). Note that in LCA, resulting latent classes are characterized by particular "conditional probabilities" representing the likelihood of providing a specific response to a given task, when a student belongs to a particular latent class. The optimal number of latent classes was ascertained using the Bayesian information criterion (BIC), in conjunction with the interpretability of the resultant solution (Collins and Lanza,

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[1] The characterization of a pictorial representation as 'complete' is connected to the 'high complexity' concept as it was introduced by Dangur et al. (2014) reporting richer and more detailed drawings (e.g., depicted dots showing electron probability density, depicted axes and angles, etc.)

Table 1: Categorization of students' responses to the first part of the tasks and relevant examples

Categories	Criteria	Example
Category SA: Scientifically Accepted	Sufficiently described "scientific" view	VerbR1: *Orbitals are wave functions ψ(x, y, z) coming from the Schrödinger equation. ψ has no physical meaning. ψ=0 indicates the absence of the electron and ψ≠0 indicates the presence of the electron. However, ψ2 is important, as it expresses the probability of finding the electron in a certain position around the nucleus* VerbR2: *The electron cloud expresses the probability to find the electron around the nucleus in a certain position. The denser electron cloud, the higher probability of finding the electron*
Category PA: Partially Accepted	Incomplete "scientific" view without including any specific misconception	VerbR1: *Orbitals are wave functions coming from the Schrödinger equation for the atomic structure* VerbR2: *The electron cloud depicts possible electron's positions around the nucleus of the atom since we do not know precisely the position of an electron*
Category PM: Partially accepted with Misconceptions	Incomplete "scientific" view including specific misconceptions	VerbR1: *Orbitals are solutions of the Schrödinger equation expressing the space in which the electron moves* VerbR2: *The electron cloud is the space in which the probability of finding the electrons is higher*
Category M: Misconceptions	Specific misconceptions including or not the probability concept	VerbR1: *Orbitals are areas where electrons can be found* VerbR2: *An electron cloud expresses the electron's distribution around the nucleus of the atom*
Category NU: No Understanding	Unclear or wrong responses - No response	

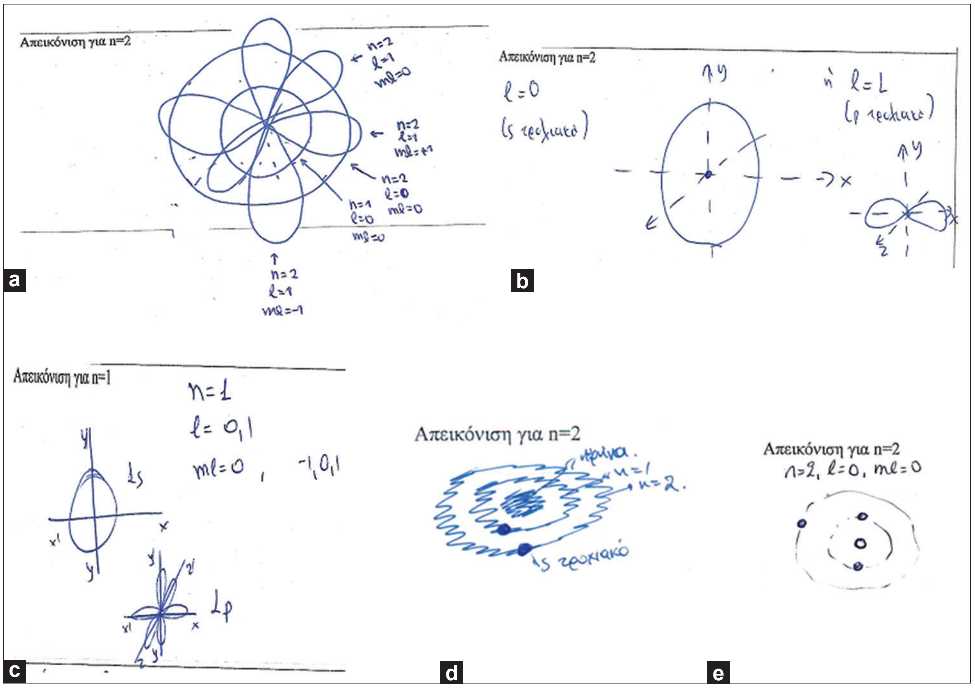

Figure 1: Some examples of students' pictorial representations, (a): level A3, (b): level A2, (c): level A1, (d): level B, and (e): level C (all cases concern orbitals)

2010), whereas bivariate residuals (BVRs) were also analyzed and the entropy value was assessed (Berlin et al., 2014).

RESULTS

Descriptive Analyses

The distribution of students across categories SA to NU for tasks related to verbal representations, specifically VerbR1 (orbital) and VerbR2 (electron cloud), is presented in Table 2, whereas Table 3 shows the corresponding distribution across categories A3 to D for tasks involving pictorial representations, namely PictR1 (orbital) and VerbR2 (electron cloud), for the values of the *principal quantum number* n = 1 and n = 2 (indicated by a and b, respectively).

Although these descriptive presentations offer an overview of the results, it is important to note that any comparisons made are subject to further analysis. However, it is evident that a significant majority of students struggle to express the concepts of orbital and electron cloud verbally, to a scientifically acceptable degree. This is reflected in the high percentage of students with relevant misconceptions, as shown in Table 2. When comparing verbal representations of orbital and electron cloud, it appears that students exhibit better competence in VerbR2 (electron cloud) compared to VerbR1 (orbital). To illustrate this, the combined number of students in categories SA and PA for VerbR1 is 66, whereas for VerbR2 it is 95. Conversely, 102 students demonstrate significant misconceptions (category M) in VerbR1, while the corresponding number for VerbR2 is 79.

Table 2: Students' numbers and percentages on verbal representations (tasks VerbR1 and VerbR2)

Category	Tasks			
	VerbR1		VerbR2	
	f	%	*f*	%
NU	-	-	2	1.0
M	102	53.1	79	41.4
PM	24	12.5	15	7.9
PA	28	14.6	43	22.5
SA	38	19.8	52	27.2

NU: No Understanding, M: Misconception, PM: Partially accepted with misconceptions, PA: Partially accepted, SA: Scientifically accepted

Table 3: Students' numbers and percentages on pictorial representations (tasks PicR1 and PicR2)

Category	Tasks							
	PicR1a		PicR1b		PicR2a		PicR2b	
	f	%	*f*	%	*F*	%	*f*	%
D	1	0.5	5	2.6	4	2.1	13	6.8
C	33	17.2	30	15.6	25	13.0	22	11.5
B	28	14.6	28	14.6	22	11.5	21	10.9
A1	7	3.6	17	8.9	38	19.8	46	24.0
A2	-	-	60	31.3	-	-	58	30.2
A3	123	64.1	52	27.1	103	53.6	32	16.7

D: No model, C: Deterministic model, B: Hybrid model, A1: Quantum model (incorrect), A2: Quantum model (correct but incomplete) and A3: Quantum model (correct and complete)

In Table 3, the student numbers suggest that their competences in the corresponding pictorial representations are relatively better compared to verbal representations. This is evident from the high percentage of students falling into categories A1, A2, and A3. However, it is unclear whether students can express orbital (PicR1) or electron cloud (PicR2) representations more scientifically accurately. For instance, although the percentage of students falling into category A3 is higher in PicR1a and PicR1b compared to PicR2a and PicR2b, the total number of students in categories A1, A2, and A3 is 130 for PicR1a compared to 141 for PicR2a, and it is 129 for PicR1b compared to 136 for PicR2b. In addition, when comparing Cases a and b, the differences in numbers are too small to draw definitive conclusions, although they suggest the expected trend that Case b is more challenging for students than Case a. This could be possibly concluded for instance, when comparing the 130 students for PicR1a to the 129 students for PicR1b and the 141 students for PicR2a to the 136 students for PicR2b in categories A1, A2, and A3 (as a sum).

Consistency between Verbal and Pictorial Representations

To examine the relationships and the consistency between students' responses to verbal and pictorial tasks, Table 4 is provided to display the distribution of categories A3 to D for pictorial representations across the categories SA to NU for verbal representations. When investigating the consistency

Table 4: Cross tabulation of student responses on verbal descriptions (rows) and pictorial representations (columns) – Number of students in each category

VerbR1	PicR1a							VerbR1	PicR1b						
	D	C	B	A1	A2	A3	Total		D	C	B	A1	A2	A3	Total
NU	0	0	0	0	0	0	0	NU	0	0	0	0	0	0	0
M	0	26	24	4	0	48	102	M	3	24	24	9	21	21	102
PM	0	3	1	2	0	18	24	PM	0	3	1	3	9	8	24
PA	1	3	2	1	0	21	28	PA	1	3	2	4	13	5	28
SA	0	1	1	0	0	36	38	SA	1	0	1	1	17	18	38
Total	1	33	28	7	0	123	192	Total	5	30	28	17	60	52	192
VerbR2	**PicR2a**							**VerbR2**	**PicR2b**						
	D	**PicR2b**	**B**	**A1**	**A2**	**A3**	**Total**		**D**	**C**	**B**	**A1**	**A2**	**A3**	**Total**
NU	0	0	1	1	0	0	2	NU	0	0	1	1	0	0	2
M	2	20	9	16	0	32	79	M	7	19	9	18	15	11	79
PM	0	1	2	6	0	6	15	PM	0	1	2	6	3	3	15
PA	1	2	6	7	0	27	43	PA	5	1	6	8	13	10	43
SA	1	2	3	8	0	38	52	SA	1	1	2	13	27	8	52
Total	4	25	21	38	0	103	191	Total	13	22	20	46	58	32	191

NU: No understanding, M: Misconception, PM: Partially accepted with Misconceptions, PA: Partially accepted, SA: Scientifically accepted; D: No model, C: Deterministic model, B: Hybrid model, A1: Quantum model (incorrect), A2: Quantum model (correct but incomplete) and A3: Quantum model (correct and complete); Significant differences are shown in bold and italics between verbal representations and pictorial representations for the value of the *principal quantum number* value n = 1 (case a), there seem to be inconsistencies for both Task 1 and Task 2. These transitions were determined to be statistically significant using Monte Carlo multinomial exact tests of symmetry ($p < 0.001$). Notably, students categorized as A3 (in both PicR1a and PicR2a) exhibit a wide distribution across categories SA to M (in both VerbR1 and VerbR2), This suggests that having a correct and comprehensive pictorial representation of atomic orbitals and electron clouds with quantum characteristics does not necessarily indicate a thorough understanding of their meaning. These transitions were consequently, students with misconceptions (category M) in both VerbR1 and VerbR2 are found across nearly all categories of PicR1a and PicR2a, respectively. These inconsistencies appear to persist even when the *principal quantum number* value is n = 2 (case b), where the inconsistency observed for A3 extends to the other A categories (A1 and A2) as well.

Consistency between Verbal Representations

Examining the consistency between student verbal representations for orbital (VerbR1) and electron cloud (VerbR2), the wide distribution across categories and the significant transitions in student responses ($p < 0.001$) indicate the presence of inconsistency. Furthermore, the findings from Table 2 support the notion that student's exhibit greater proficiency in VerbR2 compared to VerbR1. Table 5 reveals that students in category SA of VerbR2 are distributed across all categories of VerbR1 (except NU), while a considerable number of students with misconceptions (category M) in VerbR1 can be classified in higher categories (PA and SA) of VerbR2.

Consistency between Pictorial Representations

In contrast to the aforementioned inconsistencies, there appears to be consistency in the pictorial representations of Cases a and b for both Tasks 1 and 2 (Table 6). In both Tasks 1 and 2, students in category A3 of Case a, correspond to category A2 of Case b, indicating that Case b was more challenging for students compared to Case a.

On the contrary, there is a lack of consistency in the pictorial representations between Tasks 1 and 2 for both Cases a and b (Table 7). Furthermore, the distribution of category A1 in both PictR2a and PictR2b among the categories of PictR1a and PictR1b, respectively, supports the notion that pictorial representations of orbital are more likely to be accurate and comprehensive compared to the corresponding representation of electron cloud.

Student Profiles in Representational Competence

An LCA was performed to identify distinct groups of students based on their levels of representational competence in all tasks. The analysis utilized student responses from eight pictorial representation tasks as observed variables. Multiple models were estimated, ranging from one to eight latent classes, using 1000 random sets of starting values. Among these models, the four-class model yielded the lowest BIC value, indicating the best fit. This model exhibited an entropy R^2 value of 0.92 and a classification error of only 0.65%, indicating clear differentiation among the five identified student classes. Moreover, none of the bivariate residuals (BVRs) values in the four-profile model exceeded the threshold of 3.84, indicating no violations of the assumption of local independence.

Figure 2 illustrates the estimated probabilities of students offering scientifically sufficient responses to each task based on their membership in a specific cluster. Among the clusters, Class 1 (26%) showed a high likelihood of providing scientifically sufficient representations for all tasks, although the probability was slightly lower for verbal tasks compared to pictorial representations. In contrast, Class 2 (29%) demonstrated a reduced probability of providing correct answers for all tasks, except for pictorial representations PictR1a and PictR1b, where they consistently provided scientifically accurate responses. Class 3 (9%) consisted of students who were prone to misconceptions in verbal tasks but consistently provided scientifically correct answers to the pictorial tasks. Finally, the largest cluster, Class 4, representing 36% of the sample, exhibited a limited likelihood of providing scientifically adequate representations for all tasks.

DISCUSSION AND CONCLUSION

A coevaluation of findings concerning student competences in verbal and pictorial representations of both orbital and electron clouds leads to the conclusion that such quantum concepts are difficult to be understood by the students, although many differences and inconsistencies existing between these two kinds of representations makes difficult any reading and interpretation of the relevant results. Taking into account student competences solely in verbal representations, the general view tends to support the aspect that their majority fails to provide an acceptable response (PA or SA) for both orbital and electron clouds, with electron cloud appearing to be slightly more understandable compared to the orbital. However, the opposite holds true for pictorial representations, where the majority of students provides representations within the quantum model (categories A), with a mixed view comparing competences in orbital and electron clouds.

As a result, an important conclusion arises from the inconsistency found between verbal and pictorial representations. As already discussed, Table 4 provides evidence that a correct and complete pictorial representation of both orbital and cloud (category A3) cannot necessarily guarantee the sound understanding of the corresponding meaning. Although this advocates the suggestions of a number of researchers (Akaygun and Jones, 2014; Dangur et al., 2014; Ehrlén, 2009; Zarkadis et al., 2021, 2022), expressing that solely verbal or pictorial representations (separately) cannot provide us with an integrated view of what students have conceptualized of a concept in their mind, there is a different clue here compared to that we found when the concept under study was the quantum numbers (Zarkadis et al., 2021, 2022). In an opposite reading compared to those data interpretation, that is, that pictorial representations can clarify corresponding verbal descriptions of the quantum number concepts, the present study rather supports the aspect that student verbal representations of atomic orbitals and electron clouds can uncover the meaning of their pictorial representations (which could probably have drawn the way they have taught). This direction also advocates the fact that students with misconceptions in both concepts of orbital and electron cloud (Table 4, category M) can draw pictorial representations falling in almost all categories of the corresponding pictorial representations. Thus, the complementary role of verbal and pictorial representations (Ehrlén, 2009) seems to be verified when the subject of a research is what students have ultimately understood in relation to a particular concept.

Table 5: Cross-tabulation of student responses on verbal representations – Number of students in each category (tasks VerbR1 and VerbR2)

VerbR1	VerbR2					
	NU	M	PM	PA	SA	Total
NU	0	0	0	0	0	0
M	2	57	5	22	15	101
PM	0	8	6	5	5	24
PA	0	9	0	9	10	28
SA	0	5	4	7	22	38
Total	2	79	15	43	52	191

NU: No understanding, M: Misconception, PM: Partially accepted with misconceptions, PA: Partially accepted, SA: Scientifically accepted; D: No model, C: Deterministic model, B: Hybrid model, A1: Quantum model (incorrect), A2: Quantum model (correct but incomplete) and A3: Quantum model (correct and complete); significant differences are shown in bold and italics

Comparing student understanding of orbital and electron clouds, indications provided by Tables 2 and 3, seem to be verified by the findings appearing in Tables 5 and 7, respectively. That is, findings concerning student verbal representations (Tables 2 and 5) lead to the conclusion that students have verbally a better understanding of the electron cloud than the orbital, whereas those concerning their pictorial representations (Tables 3 and 7) rather lead to the opposite conclusion. At this point, only speculations could be done. For instance, it could be possible that students could more easily reproduce pictorial representations of atomic orbitals, as they have taught based on the corresponding textbook representations than verbally

Table 6: Cross tabulation of student responses on pictorial representations – Number of students in each category (tasks PicR1 and PicR2)

PicR1b								PicR2b							
PicR1a	D	C	B	A1	A2	A3	Total	PicR2a	D	C	B	A1	A2	A3	Total
D	1	0	0	0	0	0	1	D	4	0	0	0	0	0	4
C	1	30	0	2	0	0	33	C	2	22	0	1	0	0	25
B	0	0	28	0	0	0	28	B	0	0	21	1	0	0	22
A1	1	0	0	6	0	0	7	A1	4	0	0	34	0	0	38
A2	0	0	0	0	0	0	0	A2	0	0	0	0	0	0	0
A3	2	0	0	9	60	52	123	A3	3	0	0	10	58	32	103
Total	5	30	28	17	60	52	192	Total	13	22	21	46	58	32	192

NU: No understanding, M: Misconception, PM: Partially accepted with misconceptions, PA: Partially accepted, SA: Scientifically accepted; D: No model, C: Deterministic model, B: Hybrid model, A1: Quantum model (incorrect), A2: Quantum model (correct but incomplete) and A3: Quantum model (correct and complete); significant differences are shown in bold and italics

Table 7: Cross tabulation of student responses on pictorial representations – Number of students in each category (tasks PicRa and PicRb)

PicR1a	PicR2a							PicR1b	PicR2b						
	D	C	B	A1	A2	A3	Total		D	C	B	A1	A2	A3	Total
D	1	0	0	0	-	0	1	D	5	0	0	0	0	0	5
C	0	15	4	5	-	9	33	C	2	13	4	4	6	1	30
B	0	3	13	4	-	8	28	B	0	3	13	5	7	0	28
A1	0	0	0	4	-	3	7	A1	2	1	0	10	2	2	17
A2	-	-	-	-	-	-	-	A2	2	2	3	15	34	4	60
A3	3	7	5	25	-	83	123	A3	2	3	1	12	9	25	52
Total	4	25	22	38	-	103	192	Total	13	22	21	46	58	32	192

NU: No understanding, M: Misconception, PM: Partially accepted with misconceptions, PA: Partially accepted, SA: Scientifically accepted; D: No model, C: Deterministic model, B: Hybrid model, A1: Quantum model (incorrect), A2: Quantum model (correct but incomplete) and A3: Quantum model (correct and complete); Significant differences are shown in bold and italics

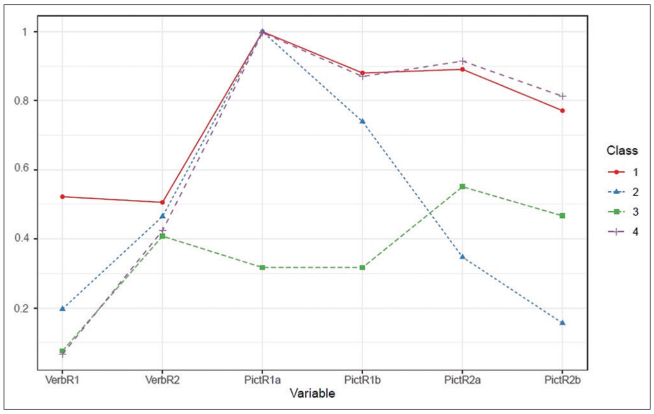

Figure 2: Four student profiles resulting from latent class analysis with the estimated probability (vertical axis) of providing a scientifically sufficient representation to each task (horizontal axis)

interpret the meaning of such pictorial representations. This could be compatible with the aspect that students cannot easily understand concepts without physical meaning like the orbital (Stefani and Tsaparlis, 2009), whereas for the electron cloud, a possible interpretation could be helped by an understanding of the concept of the density and (possibly) by the analogous of the physical cloud (in the sky).

In any case, the reliability of pictorial representation cannot be underestimated, since the consistency presented in Table 6, concerning the effect of the first quantum number on them, could be considered as a significant relevant indication. Furthermore, indications supporting that pictorial representations for n = 2 (case b) are more challenging for students compared to those for n = 1 (case a), rather converge to this aspect.

In accordance to the above, the four classes in which students can be categorized (Figure 2) can provide us with additional complementary information. Thus, a more complete view for the relevant students' representations could be shaped taking into account that only 26% of students could be categorized in Class 1, providing scientifically sufficient representations for all tasks, in contrast to 29% of them, who are categorized in Class 2 with a reduced probability of providing correct answers for all tasks, and 36% of them, who are categorized in Class 4 with a limited likelihood of providing scientifically adequate representations for all tasks. Furthermore, compatibly to the above, the probability for scientifically sufficient representations was slightly lower for verbal tasks compared to pictorial representations (class 1) and students who had misconceptions in verbal tasks could consistently provide scientifically correct answers to the pictorial tasks.

Implications for Science Education

In accordance to the discussion above, implications for the teaching and learning procedure could be drawn in relation to the concepts of orbital and electron cloud. On the one hand, since pictorial representations appear to be once again consistent tools (Zarkadis et al., 2021, 2022) independently of the quantum context (the value of the principal quantum number n = 1 or n = 2), they could be used as a basis for the teaching methodology concerning both concepts. On the other hand, the findings of the study indicate the need of clarifications of students' pictorial representations on the basis of their verbal representations, advocating the suggestion of many researchers (Akaygun and Jones, 2014; Dangur et al., 2014; Ehrlén, 2009; Zarkadis et al., 2021, 2022) for the complementary nature of these two kinds of representations.

As a result, both verbal and pictorial approaches seem to be necessary when either orbital or electron cloud concepts are taught in the classroom. Teachers have to understand for instance, that pictorial representations provided by the textbooks can only partially contribute to the students' conceptualization of such concepts, whereas a holistic approach requires also verbal interpretations of what students can see in the corresponding pictorial representations. Toward the same direction, any tool designed for the assessment of either orbital or electron cloud concepts should also take into account the necessity of using both kinds of representations. This concerns not only teachers, who are seeking to evaluate their students' performance but also researchers, who are trying to understand students' conceptualization of relevant quantum concepts.

Limitations

A restriction of the generalization of the findings should be acknowledged due to the limited geographical context in which the study took place and the sample size, which was relatively small. Furthermore, the coding scheme applied during the analyses of the students' pictorial representations is subjected to the researchers' perceptions; the cross-sectional design of the study excludes representations causal inferences, whereas a possible data triangulation with student interviews could provide additional explanations for their representations. Thus, further research is probably needed to clarify the role of each one of the two kinds of representation (verbal and pictorial) to a more integrated view concerning students' understanding of such quantum concepts.

INFORMED CONSENT

Informed consent was obtained from the heads of the participating schools, the teachers of all classes, and the students before the study.

DISCLOSURE STATEMENT

There are no conflicts to declare.

ETHICS STATEMENT

The study was approved by the Department of Primary Education of the Democritus University of Thrace, Greece, in accordance with guidelines provided by the Institution's Ethics Committee.

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