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Students' Conceptual Difficulties of some Selected Coordination Chemistry Topics in Higher Education

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ABSTRACT
This study assessed the conceptual gains of students of some topics in coordination chemistry. A case study design within the Model of Educational Reconstruction approach was used. The accessible population was all third-year chemistry students in the University of Education, Winneba (UEW)-Ghana with sample size of forty-six (46) students. The study involved students in a class of 9 groups, comprising 5-6 students each over eleven-week period. The students' conceptual understanding was assessed in pre-and post-tests through effect size measurements using the Cohen and the Sawilosky's 'h' parameters. The findings among others showed that students had some conceptual difficulties in the selected topics in coordination chemistry.
Keywords: educational reconstruction, conceptual gains, coordination chemistry, effect size

INTRODUCTION
The study was based on the philosophy reiterated by Lakoff and Johnson (1999). According to these authors, when scientists and students communicate with the same words, they do not necessarily communicate the same concepts. Empirical evidence also indicates that even if students and scientists explain the same concept using identical terms/words, they do not attach the same meanings to the terms. Considering this situation of citing/fusing students and scientists' conceptions to improve learning of coordination chemistry in higher education, the 'negotiating meaning to engender understanding' principle was greatly relevant in this study. This principle herein opened up another door into concept-word(s) expression. In this manner, the study showed that 'concepts are what words express', citing in general that the terms we use to describe specific aspect of concept (nomenclature and geometry, isomerism, bonding and metal colours) engender our understanding of the concept, be used/expressed with caution.
Thus, this study reiterated that both scientists and students cannot simply change words without changing meaning. With this in mind, the researcher needed and used clear and simple but content-specific scientific word expressions for the students. The research undertaken on students'/scientists' (conceptions) showed that teaching and learning coordination chemistry was not only connected to students' prior conceptions but also emanates from or hinges on learners' prior experience. Satisfying students' learning demands was a great thing to consider by providing accessible and comprehensible information on the topics to be treated in the classroom. There was therefore the need to analyse not only the students' pre-instructional conceptions but also the experiential basis for the concept to be taught, considering the following facts:

1. The usefulness of the content structure linking the practical needs of the students;
2. Testing, developing and refining content oriented local theories; and
3. Fusing investigations and classroom interventions as research at the same time.

The main conceptual framework used for the study was the Model of Educational Reconstruction (MER) – that is, how students' knowledge influence cognitive reconstruction (Duit et. al., 2012). Some researchers have used the MER to conduct studies into topics such as metal-ligand geometries (Sam, Eminah, Hanson, & Raheem, 2019), metal complex isomerism (Sam, Niebert, Hanson, & Aryeetey, 2016), coordination chemistry (Sam, Niebert, Hanson, & Twumasi, 2015), climate change (Niebert & Gropengiesser, 2013), evolution (Zabel & Gropengiesser, 2011), and a few others. These studies demonstrated a successful content oriented educational research through the MER principles.

The objectives for this study were to:

- Assess students conceptual difficulties associated with each of the selected topics in coordination chemistry
- Evaluate students' conceptual gains of the selected aspects in coordination chemistry resulting from the reconstruction process?

The study was guided by the following research questions:

1. What measure of conceptual difficulties did the students associate with each of the selected topics in coordination chemistry?
2. What gains in the students' conceptual understanding of the selected aspects in coordination chemistry resulted from the reconstruction process?

METHODOLOGY

The study was a case study using the Model of Educational Reconstruction (MER), approach as proposed by Niebert and Gropengiesser (2013). This approach was adapted in this study because it is a widely used research approach which seeks to improve content-specific learning and teaching. Furthermore, the research design was based on the MER due to its inherent ability to improve science teaching from secondary to higher education when adopted. The quantitative methodology with the Cohen and Sawilosky's "h" was used to calculate the *effect size* between the pre- and the post-tests administered to the students in the study. Students' responses were categorised as *small and very small understanding*, when the study found these conceptions to be incorrect with inappropriate reasoning (Rushton, 2008). Students' correct answers with alternative conceptions or incorrect comments were assigned *medium understanding*. Students' right or correct conceptions with appropriate reasoning represented a *large or very large understanding*.

Population

Participants in the study were all third-year chemistry students in the University of Education, Winneba (UEW), who took the coordination chemistry course in the second semester of the 2018/2019 academic year. There were forty-six (46) students involved. The 46 comprised forty-one males and five females in the study.

Sample selection procedure

Purposive sampling was used for all the forty-six (46) third year chemistry students for the study. According to Creswell, (2008), in this type of sampling, the researcher determines the type of participants who are appropriate for the study and select them. Based on this, the third-year chemistry students of the University of Education of Winneba were the accessible population for this study. They were randomly assigned to groups. The simple random technique was used by urging the participants one at a time to pick one coloured ball in a brown enclosed envelope. Each of the participants was to pick a coloured-ball and show it to the class. All those having the same coloured-balls were put in one group. Members in each group were then given specific tasks designed by the researcher, who served as the instructor for the course. This relationship enhanced easy administration and the collection of data for the study. In a class session, students were given ten (10) written pre-test items in twenty (20) minutes to answer. These students' difficulties were corrected after the introduction of the interventional strategies adopted (that is, Science Writing Heuristics & Modelling and Modelling Skills). Delayed subjective post-test items of similar contents were administered to the students after two (2) weeks using a pen and paper.

Instrumentation

With the purpose of the study in mind, it required that data be collected on

(i) Pre- & post-tests with pen and paper
(ii) Students' drawings of metal complexes.

Validity of the instrument

Two experts in the field of inorganic chemistry validated by marking (using a marking scheme prepared by the first author) the students' responses independently. In this activity, the written (pen and paper tasks) responses were read several times, analysed and summarised independently by the two researchers. The agreement between the assessments was 70% and with the few cases of discrepancies, the researchers made a common assessment after discussions.

RESULTS AND DISCUSSION

Research Question 1: ***What measure of conceptual difficulties did the students associate with each of the selected topics in coordination chemistry?***

The goal of this research question was to measure the conceptual difficulties of the students by determining the extent to which the students could both recall and express their views correctly, and to identify the common alternative ideas they held about these conceptions. The measure of students' conceptual difficulties was based on the idea initiated by Lakoff and Johnson (1999) that "understanding is fruitful through negotiation of meaning". This theoretical philosophy supported by the Cohen and Sawilowsky "h" formula on *effect size*, helped the researcher to address research question one (1).

Students' achievement in the classroom discourse on nomenclature and geometry for both the pre- and the post-concepts is expressed in Table 1. For comparing the magnitude of change (*Effect Size*) on this theme, the Cohen and Sawilosky's 'h' was used to better express and explain the differences between the themes stated in Table 1.

Table 1*: Effect size distribution on nomenclature and geometry*

Nomenclature and Geometry				
Themes	Pre-concepts	Post-concepts	Cohen & Sawilosky's 'h' [a]	Effect Size
Charge ion/ionic properties	13.33	23.08	0.26	*Small*
Dimensionality of molecules	20.00	34.62	0.33	*Small*
Donor atom specification	20.00	15.38	-0.12	*Very small* [b]
Names of ligands in coordination entities	6.67	11.54	0.17	*Very small*
Metal names	6.67	3.85	-0.13	*Very small* [b]
In/out metals in coordination entities	6.67	11.54	0.17	*Very small*
Prefix omission	0.00	0.00	-	-
Unorthodox explanation(s)	26.67	0.00	-1.09	*large* [b]

[a] Cohen's 'h' = 2 arcsin (percent $^{0.5}$ post-concept) – 2 arcsin (percent $^{0.5}$ pre-concept)

[b] Indicates items for which the post-concepts underperformed the pre-concepts

Note: The arcsin is the $\sin^{-1}$ in radians

Source: Researcher's construct 2018

Table 1, shows the magnitude of the differences in the pre- and post-concepts on nomenclature and geometry of coordinated compounds. The effect size used were the Cohen (1988) and Sawilowsky (2009) combined effect size tables, where 'h' values between 0.01 and 0.19 are very small, those between 0.2 and 0.49 are small, those between 0.5 and 0.79 are medium, those between 0.80 and 1.19 are large, those from 1.20 to 1.99 are very large whilst those above 2.0 are huge.

As seen in Table 1, the students' post-concepts were better than their pre-concepts. To some extent this could be associated with the relative and partial use of the interventional strategies introduced in the course. It was interesting to note that on two of the themes: that is 'donor atom specification' and 'metal names', the students' pre-concepts were greater than their post-concepts, and that both themes are typically taught elsewhere in the chemistry curriculum in addition to coordination chemistry. Similarly, the students' post-concepts on unorthodox explanation(s) were better than the pre-concepts. This can be explained by the fact that, students after experiencing with the scientific heuristics and the chemical models reduced their unscientific comments to a more appropriate scientific explanation to questions given them. This showed in Table 1, where there was a 'maximal' change of 1.09, indicating a very large difference in conceptual understanding.

Students' response differences in their post- and pre-concepts on geometrical isomerism are expressed in Table 2, using effect size.

Table 2*: Students' effect size distribution on geometric isomerism*

	Geometric Isomerism			
Themes	Pre-concepts	Post-concepts	Cohen & Sawilosky's 'h' [a]	Effect Size
Octahedral	5.56	29.41	0.67	*Medium*
Cis/trans-rearrangement	22.22	35.29	0.30	*Small*
Symbolic representation	27.78	29.41	0.04	*Very small*
Unorthodox explanation(s)	44.44	5.88	-0.97	*Large* [b]

[a] Cohen's 'h' = 2 arcsin (percent $^{0.5}$ post-concept) – 2 arcsin (percent $^{0.5}$ pre-concept)
[b] Indicates items for which the post-concepts underperformed the pre-concepts
Note: The arcsin is the $\sin^{-1}$ in radians

Source: Researcher's construct 2018

From Table 2, students' responses at the post-concepts stage were considerably better than their responses at the pre-concepts stage. There was a marginal increase in the students' understanding of octahedral representations of coordinated structures - about 0.67, showing medium understanding. Additionally, students' post-concepts on unorthodox explanations were good compared to their pre-concepts. This the researcher, can explain as the students losing grasp of their unscientific ideas on geometrical isomerism, leading to a large effect size. The students also had prior experiences with cis/trans rearrangements and symbolic representations in the pre-concepts but were slightly reviewed by a small feed of effect. However, model confusion in general was witnessed in introductory and first-time chemistry courses such as coordination chemistry and, as Taber described, results from formal learning environments (Taber, 2002). The researcher herein explained this effect as the students' have had prior and basic knowledge of cis/trans experiences of molecules and symbolic representations in some organic chemistry courses. Topics such as stereochemistry, conformers and placement of substituents (that is, either axial or equatorial) might have reinforced these situations.
The basis for understanding bonding and colours exhibited by some coordinated compounds is expressed in Table 2. Students' pre- and post-conceptual values on bonding and colours are stated in Table 3 for easy interpretation.

Table 3: *Students' effect size distribution on bonding and colours*

	Bonding and Colours			
Themes	Pre-concepts	Post-concepts	Cohen & Sawilosky's 'h' [a]	Effect Size
Colour appearance	25.00	13.16	-0.31	*Small* [b]
Hybridisation	33.33	26.32	-0.15	*Very small* [b]
Spectrochemical series	0.00	26.32	1.08	*Very large*
Splitting energy (t_2g & eg)	0.00	10.53	0.66	*Medium*
Electron configuration	33.33	10.53	-0.57	*Medium* [b]
Type of ligand(s)	0.00	10.53	0.66	*Medium*
Unorthodox explanation(s)	8.33	2.63	-0.26	*Small* [b]

[a] Cohen's 'h' = 2 arcsin (percent $^{0.5}$ post-concept) – 2 arcsin (percent $^{0.5}$ pre-concept)
[b] Indicates items for which the post-concepts underperformed the pre-concepts
Note: The arcsin is the $\sin^{-1}$ in radians

Source: Researcher's construct 2018

As seen in Table 3, the post-concept themes on colour appearance, hybridisation and electron configuration were smaller than the pre-concepts whilst the post-concepts in themes such as the spectrochemical series, the splitting energy and the type of ligands used in bonding were greater than the pre-concepts. The relationship between the themes stated earlier and the latter in the study is that, the students' demonstrated familiarity with topics such as hybridisation, colours and electron configurations in their previous general chemistry and introductory organic chemistry courses. It was found out that students had little or no knowledge on topics such as spectrochemical series; the splitting energy and ligand types (that is, strong field or weak field) and therefore needed higher conceptual understanding in such topics to enable them predict correctly the colours to be exhibited by coordinated compounds. From Table 3, it is evident, as the students gave no pre-concepts comments on these themes.

Research Question 2: ***What gains in the students' conceptual understanding of the selected aspects in coordination chemistry resulted from the reconstruction process?***

This research question focused on the gains of the students' conceptual understanding and also on the description of their strengths and weaknesses in the learning activities. This insight bore important consequences on the instructional interventions (Modelling and Modeling Skills, MMS and Science Writing Heuristics, SWH) carried out in earlier studies. Reflection on how understanding is to be achieved is far more challenging than practice (Niebert & Gropengiesser, 2013). To help the students to understand nomenclature and geometry, scientists' conceptions were necessary for adequate practice, especially those that originated from the four (4) textbooks used. The researcher organised meaningful experiences (that is the coded-themes) for the students that were aimed at provoking thoughts on their specific conceptions. By evaluating the respective sub-coded themes in the teaching activities, the researcher was able to follow the students' conceptual development (gains) and describe their strengths and weaknesses in the learning activities.

In this study, the researcher neither judged the conceptions raised by the students as wrong nor looked for external sources, such as other books apart from the textbooks used for the research work. In a way, the researcher expressed how the students and scientists employed their conceptual resources in an attempt to understand coordination chemistry (nomenclature and geometry). Furthermore, the quantitative frequency percentage count(s) allowed the researcher to open a window to interrogate students' and scientists' conceptual resources needed to understand nomenclature/geometry, isomerism, bonding and colours of metal complexes. A summary of the comparative percentage count(s) of the sub-coded items is represented in Table 4.

Table 4: ***Comparative conceptions on nomenclature and geometry***

Sub-code(s)	Students' pre-concepts in %	Scientists' concepts in %	Students' post-concepts in %
Charge ion/ionic properties	13.33	23.08	23.08
Dimensionality of molecules	20.00	23.08	34.62
Donor atom specification	20.00	15.38	15.38
Names of ligands in coordination entities	6.67	15.38	11.54
Metal names	6.67	15.38	3.85
In/out metals in coordination entities	6.67	7.69	11.54
Prefix omission	0.00	0.00	0.00
Unorthodox explanation(s)	26.67	0.00	0.00
Total	100.00	100.00	100.00
Missing	0.00	0.00	-
Total	100.00	100.00	-

Source: Researcher's construct 2018

From Table 4, the individual contributions towards the themes underpinned the different conceptions expressed by both the students and scientists in understanding the nomenclature and the geometry of complexes. These contingencies of different views shared by the participants were expressed as thinking patterns (trends) on the themes as how individual and variable construction of knowledge would support conceptual understanding. Students' post-conceptions on molecule dimensionality were expressed to be about 34.62%. On the charge ion/ionic properties sub-theme, students were expected to calculate and predict the oxidation states/numbers of the central metal in the given complexes. These formed variant conceptions amongst the students. Students' post-concepts in predicting oxidation numbers were 23.08% being the same as the scientists' conceptual view. Students' pre-concepts in metal naming, ligand names and metals in/outside the complexes were the same, about 6.67%, but these conceptual resources increased to about 11.54% in the post-concepts, with only a decrease in the metal naming (3.85%). Surprisingly, no conceptions were generated on the ligand prefixes: from all the participants. This showed a complete conceptual knowledge, understanding and usage of ligand prefixes (such as tri, tetra, and penta) by the students. These constructions of knowledge, not in literature and totally not in-line with scientific views, were termed as unorthodox concepts. Within the categorisation of these themes and comparing students' pre-concepts on naming and geometry to the conceptual resources from the scientists, the unorthodox concepts extracted were 26.67%. These unorthodox resources thereby dwindled to about 0.00% after the introduction of key interventions (MMS and SWH) on nomenclature and geometry. The conceptual views from the participants have been illustrated in Figure 1 for easy comprehension.

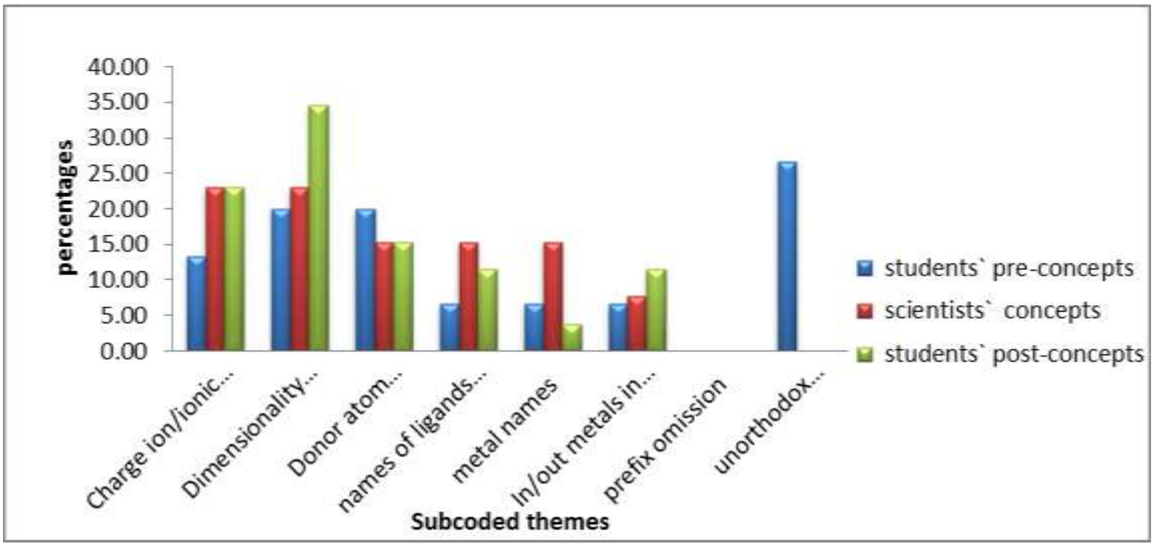

***Figure 1*: Comparative analysis of participants' ideas on nomenclature and geometry**

The graph in Figure 1 showed that, students' post-conceptual ideas on the sub-themes were linked closely to the scientists' concepts that were formulated in the reconstructive process into the content structure for instruction. The study realised a parallel analysis of students and scientists' conceptions on nomenclature and geometry that were beneficial for the investigational and interventional tasks. From Figure 1, these tasks sharpened students' pre-concepts into bringing close similarities and gains in/between the post-concepts and the science perspectives.

The conceptions on isomerism emerged through individual applications of semantic compositions and different explanation(s) generated by the students in Table 5.

Table 5: ***Comparative conceptions on isomerism***

Sub-coded themes	Students' pre-concepts in %	Scientists' concepts in %	Students' post-concepts in %
Octahedral	5.56	42.86	29.41
Cis-/trans- rearrangement	22.22	28.57	35.29
Symbolic representation	27.78	28.57	29.41
Unorthodox explanation	44.44	0.00	5.88
Total	100.00	100.00	100.00
Missing	0.00	0.00	-
Total	100.00	100.00	-

Source: Researcher's construct 2018

From Table 5, the extracted versions on the isomeric concepts were octahedral conceptions, cis/trans-rearrangements, symbolic representations and unorthodox concepts. The students' pre-concepts about unorthodox explanations on isomers were 44.44% whilst this dwindled to 5.88% in the students' post-conceptual expressions. This showed a tremendous improvement of the students' conceptual ideas about geometric isomerism. The cis/trans rearrangement, expressed as the post-concepts by the students was 35.29%. The students in this category could now discern isomeric re-arrangement through rotations and transforming the 3-D figures into 2-D structures on paper. By working in groups and re-experiencing the SWH, the students were able to raise their post-concepts on symbolic representations to about 29.41%. This was slightly above the scientific view of about 28.57%. As the students reflected on how they employed in their effort to understand concepts on octahedral complexes, the post-concepts improved to 29.41%. This was a positive shift from initial pre-concepts of 5.56%. For easy understanding and interpretation, the study herein represented these quantified scores in Figure 2.

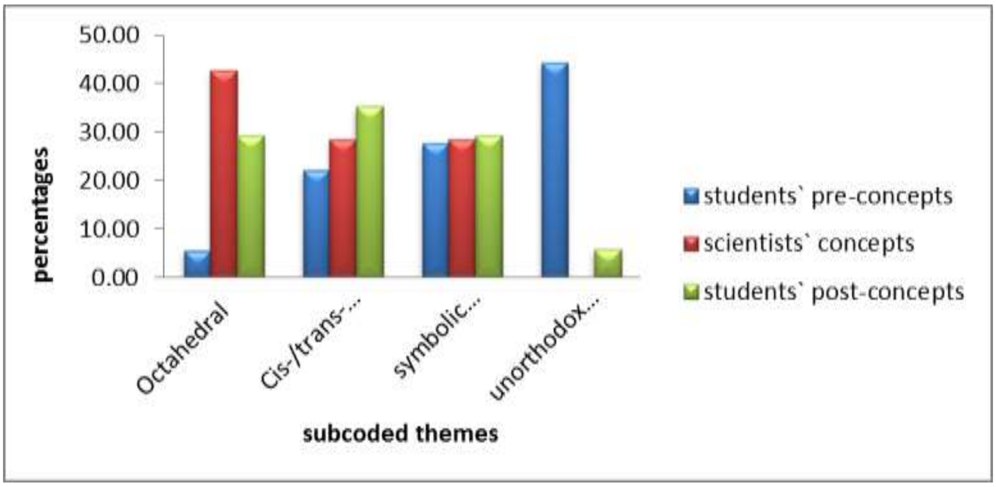

***Figure 2*: Comparative analysis on isomerism**

From Figure 2, it became evident that students' pre-concepts, scientists' concepts and students' post-concepts on symbolic representations were almost the same. The use of the SWH/the MMS and self-reflections, helped the students to increase their conceptual understanding of the cis/trans re-arrangement on geometric isomers to about 15.07%. Consequently, this shaped the conceptual understanding of the students by accepting and reviewing their unorthodox explanations assigned to isomeric structures. The instructional documents supplied to students were therefore comprehensible, accessible and comprehensive. These were operationalised by relating the instructional materials to the students' conceptual resources in the design to improve the learning environments. This in Figure 2 showed a reflection of students' post-concepts on geometric isomerism being skewed to the right, closer to the scientists' conceptions.

To analyse how and whether learning environments influenced students' conceptions; the study evaluated the learning environments in teaching activities (experiments). These teaching activities provided empirical opportunities to combine students' investigational pre-concepts with the interventional post-concepts. Analysis of students' pre-concepts, scientists' concepts and students' post-concepts on bonding and metal colours are represented in Table 6. This table contains information on students' pre-concepts and their development in the course of instruction on the topic: Bonding and colours of metal complexes.

Table 6: ***Comparative conceptions on bonding and colours***

Sub-coded themes	Students' pre-concepts in %	Scientists' concepts in %	Students' post-concepts in %
Colour appearance/complementary colours	25.00	23.53	13.16
Hybridisation	33.33	17.65	26.32
Spectrochemical series	0.00	17.65	26.32
Splitting energy	0.00	17.65	10.53
Electron configuration	33.33	11.76	10.53
Type of ligand(s)	0.00	11.76	10.53
Unorthodox explanation	8.33	0.00	2.63
Total	100.00	100.00	100.00

Source: Researcher's construct 2018

From Table 6, students considered only three (3) basic themes in their pre-concepts as basis for the bonding in metals and exhibition of colours. The pre-concepts used by students were hybridisation (33.33%), electron configuration (33.33%) and colour appearance (25.00%). It was found that students only viewed 'surface' similarities between the source (hybridisation) and the target (bonding). They needed to be aided in describing similarities and dissimilarities between the analogue and the target concepts in constructing adequate conceptions. The study approach needed to negotiate meaning to formulate understanding on the topic. Colour exhibition by metal complexes was dependent on the type of ligand(s) (either weak field or strong field) involved in bonding, the splitting energy and the spectrochemical series. Students in the first batch (pre-concepts) never considered these effective contributors to the colour generated but rather concentrated on hybridisation, electronic configuration(s) and unorthodox expressions in their explanations. Introducing the colour wheel and the spectrochemical series chart helped the students to better sharpen their conceptual resources (understanding). This provided them with the opportunity to think through their acquired second-hand scientific knowledge on bonding and metal colour exhibition. Students' post-concepts in the areas of the spectrochemical series theme (26.32%), splitting energy (10.53%) and the ligand types (10.53%) were greatly considered as equally and more important as reiterated by scientists. These variable conceptions on bonding and colours are represented as Figure 3.

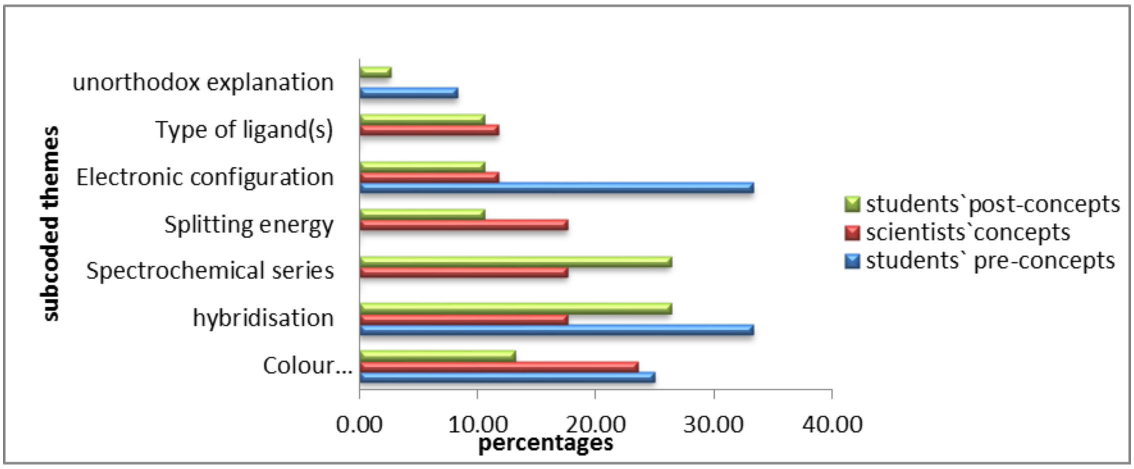

Figure 3**: Comparative analysis of the scientists/students' views on bonding and colours**

A summary from Figure 3 showed that both scientists and the students' post-concepts considered the type(s) of ligand, the spectrochemical series, splitting energy as means and contributors towards colour production in metal complexes. Hybridisation and electron configuration of the central metal were stated by the students as the main themes to consider in bonding.

CONCLUSIONS

It was found that students had no or little knowledge in topics such as spectrochemical series; the splitting energy and ligand types (that is, strong field or weak field) and therefore needed higher conceptual understanding of such terms to enable them predict correctly the colours exhibited by coordinated compounds. The students showed adequate understanding of chemical formulae, formation of compounds, bonding and hybridisation of metal complexes; and writing names of metal complexes.

The students also discerned isomeric re-arrangement through rotations and transformation of the 3-D figures into 2-D structures on paper and vice versa. By working in groups and using the SWH and the MMS, the students were able to raise their post-concepts on symbolic representations to about 29.41%. The students developed the competencies of calculating and predicting oxidation states of central metals, recognising and identifying molecular dimensions, naming ligands in coordination entities; and distinguishing metals located in and outside coordination spheres.

RECOMMENDATIONS

The study herein suggests to teachers and instructors in the field of inorganic chemistry to allow students reflect on their conceptions, as this is important to activate students' prior knowledge and experience. This study showed that conceptual reasoning engagements could be a good way of giving the students opportunities to express themselves. Guided by this, instructors are encouraged and advised to primarily be interested in how and why students understand what they understand and express them in their own way.

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