A Cross-Age Study On The Understanding Of Basic Inorganic Chemistry Qualitative Analysis

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Kim Chwee Daniel, Tan.

Nanyang Technological University, Singapore

Abstract: This cross-age study sought to determine the extent of secondary students' (14-17 years old), junior college students' (16 to19 years old), and graduate in-service teachers and trainee-teachers' understanding and alternative conceptions of basic inorganic chemistry qualitative analysis. The results from the administration of the two-tier multiple choice Qualitative Analysis Diagnostic Instrument (QADI) showed that there was a statistically significant difference in mean scores across educational levels – as expected, the in-service teachers and trainee-teachers obtained the best results, followed by the junior college and the secondary students. However, the mean scores of the graduates (9.9/19), junior college students (8.1) and secondary students (5.8) showed that they found the QADI difficult. The cross-age study showed that many alternative conceptions were prevalent among the different groups but were consistently held by only a small number of subjects (0-23%) across all contexts examined in the QADI. These results indicated that the subjects might have more than one conception for a particular concept, or had little understanding of qualitative analysis and resorted to guesswork. The present chemistry practical assessment system in which only students' written reports are assessed and marks mainly allocated to correct observations could be the major factor influencing students' lack of understanding of QA.

Introduction

The topic, qualitative analysis (QA) requires students to carry out a series of procedures using chemicals, apparatus and appropriate techniques, observe and record what happens, and make inferences based on their observations. QA is a difficult topic for secondary chemistry students (Tan et al., in press), possibly because of the content of the topic (White, 1994), the lack of appropriate frameworks (Tasker & Freyberg, 1985; Duit & Treagust, 1995), the lack of cognitive strategies (Gunstone, 1994; Wittrock, 1994), cognitive overloading (Johnstone & Wham, 1982; Nakhleh and Krajcik, 1994) and the lack of mastery of process skills (Goh, Toh & Chia, 1987; Herron, 1996).

In order to do well in QA practical work, students should have a conceptual understanding of the underlying reactions. This conceptual understanding can be evaluated by two-tier multiple choice diagnostic instruments (Treagust, 1995). Using this approach, the first-tier choices examine factual knowledge while the second-tier choices examine the reasons behind the first-tier ones. To ensure the validity of the diagnostic instrument, the propositional knowledge is to be specified clearly, and the items in the instrument are to be developed based on known student conceptions, student-drawn concept maps and responses from students to interviews and free response items. This methodology has been used to develop diagnostic tests on photosynthesis and respiration (Haslam & Treagust, 1987), and diffusion and osmosis (Odom & Barrow, 1995) in biology; in chemistry, diagnostic instruments have been developed for covalent bonding (Peterson & Treagust, 1989; Peterson, Treagust, & Garnett, 1989), chemical bonding (Tan & Treagust, 1999), chemical equilibrium (Tyson, Treagust, & Bucat, 1999) and qualitative analysis (Tan, 2000).

Purpose

This study sought to determine the extent of secondary (Grade 10) students' (15 to 17 years old), junior college (Grade 11 and 12) students' (16 to 19 years old), and graduate in-service teachers' and trainee-teachers' understanding and alternative conceptions of the concepts and propositional knowledge related to qualitative analysis as measured by the Qualitative Analysis Diagnostic Instrument (QADI) (Author, 2000). Examples of items in the QADI are given in the Appendix. This comparison was conducted to examine the retention of the alternative conceptions on qualitative analysis over time, and to determine if and when the alternative conceptions disappeared (Birk & Kurtz, 1999). Cross-age studies are subjected to the error of comparing nonequivalent populations, but are more easily accomplished and have been used in previous studies on student understanding of science concepts (eg., Abraham, Williamson, &

Westbrook, 1994; Birk & Kurtz, 1999).

Method And Procedures

The instrument

The two-tier multiple choice Qualitative Analysis Diagnostic Instrument (QADI) was developed in three phases using procedures defined by Treagust (1995). The first phase involved defining and validating the content framework of the General Certificate of Education Ordinary Level (O-level) inorganic chemistry qualitative analysis. The O-level examination is a national examination that secondary students in Singapore take at the end of Grade 10. The second phase involved the identification of secondary students' alternative conceptions of qualitative analysis through interviews and free-response written tests. The data collected in the first and second phases contributed to the development of the first version of the two-tier multiple choice instrument that was used in the third phase. Further trials and refinement led to the development of the QADI. The content validity of each of the 19 items in the QADI was established by four senior secondary chemistry teachers and three tertiary chemistry professors.

The subjects

The QADI was administered to 915 Grade 10 students from 11 secondary schools, 360 junior college students from three junior colleges, and 81 graduate trainee-teachers and 17 in-service graduate teachers. Most of the trainee-teachers had degrees in chemistry, material science or chemical engineering, and would be teaching secondary chemistry after their Postgraduate Diploma in Education (PGDE) course. The in-service teachers were teaching chemistry in secondary schools and were attending a course in 'Creative Teaching in Chemistry' in the same institution which conducted the PGDE course. The Grade 11 and 12 junior college students were treated as one group, and the trainee-teachers and in-service teachers also were treated as one group.

Administration and scoring of the QADI

The subjects were instructed to answer the items in the QADI without any discussion. A data sheet containing notes on QA given to Grade 10 students during the O-level practical examinations was provided with the QADI for all subjects to refer to during the test. There was no time restriction for the test, and on the average, subjects took between 45 to 60 minutes to complete the QADI.

The subjects' answer sheets were marked using an optical mark reader, and their results were analysed using SPSS version 9 (SPSS, 1999). Each item was considered to be correctly answered if one correctly responded to both parts of the item (Peterson & Treagust, 1989; Peterson et al., 1989).

Results And Discussion

Test statistics

Test statistics for the various groups are given in Table 1. The mean scores of the various groups were low; the lowest mean score was 30% (Grade 10 students) and the highest mean score was 52% (trainee-teachers). A one-way analysis of variance (ANOVA) was conducted to determine the effect of educational level on the scores showed that the mean total scores across educational levels were statistically significantly different ($p<.001$) (Table 2). A post hoc pairwise multiple comparisons analysis (Tamhane) was conducted (Table 3) to determine the mean total scores of which educational levels differ significantly.

Tables 1, 2 and 3 about here

The graduate trainee-teachers and in-service teachers would have a minimum of seven years of formal chemical education, the junior college students between three to four years, and two years for the Grade 10 students. Thus, based on the number of years of chemical education, it was expected that the results of the graduates would be better than that of the junior college students, and that the results of the junior college students would be better than that of the secondary students (G > JC > Sec 4 (Grade 10)), and this was the case (Tables 2 and 3). Thus, it was possible to conclude that understanding of basic qualitative analysis concepts as measured by the QADI increases with educational level. In addition, the coefficient alpha value was highest for the graduates (0.81) and lowest for the secondary students (0.68) – this could indicate that the greater the exposure to chemical education, the lesser the likelihood of guessing and leaving any question or part of a question unanswered.

The percentages (20% or more) of secondary students, junior college students and graduates selecting response combination for each item in the QADI are shown in Table 4. The large number of responses with less than 20% of subjects choosing them indicated that they were not attracted to these and might be guessing. In every item, the highest or second highest responses were the accepted options indicating that there were sizeable percentages of subjects who understood the basic QA tested by the QADI. Thus, the items worked effectively in diagnosing their learning.

Table 4 about here

Alternative conceptions

The alternative conceptions identified from the results of the administration of the QADI to the Grade 10 and junior college students, trainee-teachers and in-service teachers were grouped under the same headings of 'Displacement', 'Redox', 'Addition of acid', and 'Heating' in Table 5. Figures below 20% are not presented as in this paper, the alternative conceptions are considered significant only if they existed in at least 20% of a given sample (Peterson et al, 1989; Peterson & Treagust, 1989). Options A4 and A5 in Questions 2 and 4, respectively, were not considered as alternative conceptions because the authors decided not to consider stating that a precipitate dissolved in a reagent because it formed a soluble compound with the reagent as an alternative conception. Though the term 'dissolve' was inappropriately used in this situation, the authors believed that the students understood what had occurred leading to the disappearance of the precipitate, and agreed with Brosnan (1999) that understanding of the phenomenon in this case was more important than the terms used to categorise the phenomenon.

Table 5 about here

As with the cross-age study by Abraham et al. (1994), there were no predictable patterns in the frequency of alternative conceptions with respect to educational levels in this study, though in general, the percentage of graduates having alternative conceptions was the lowest, followed by junior college students and secondary students. Many alternative conceptions still existed despite exposure to increasing chemical education, for example, the 'reactive ion displacing a less reactive ion' alternative conception (A1 and A4 of Item 5) was still prevalent among the advanced chemistry subjects. Ammine formation (Item 8) and, to a lesser extent, complex salt reactions (Item 3 and 15) were not well understood by all three groups, as well as the purpose of adding acid after the introduction of aqueous barium or silver nitrate (V) and the reactions involved (Items 12 and 17).

Thus, the prevalence of alternative conceptions among the advanced chemistry subjects showed that there were common conceptions among the different educational level subjects, and that the alternative conceptions were retained (Abraham et al., 1994; Birk & Kurtz, 1999; Osborne & Cosgrove, 1983; Palmer, 1999; Posner et al., 1982; Watson, Prieto, & Dillon, 1997). These findings could indicate that many of the advanced chemistry subjects still had an instrumental understanding of the procedures in qualitative analysis, or were unable to apply their additional knowledge to the understanding of qualitative analysis procedures and reactions as measured by the QADI.

Consistency of alternative conceptions

A statistical analysis was carried out to determine the consistency of the alternative conceptions (Birk & Kurtz, 1999). For example, the alternative conception 'a more reactive ion displaces a less reactive ion in a double decomposition reaction/precipitation mixture' had four questions with content-reason pairs pertaining to it. The extent to which the subjects believed each alternative conception was determined by calculating percentages based on the number of times each subject picked a content-reason combination that supported that alternative conception. Thus only alternative conceptions which appeared in more than one question were analysed. This ruled out all of the alternative conceptions under the categories 'Redox' and 'Heating', and a few in the other categories. The percentage of subjects who selected content-reason pairs supporting each alternative conception 75% of the time or more (Birk & Kurtz, 1999) is shown in Table 6.

Table 6 about here

It can be seen from Table 6 that with one exception, only a small extent (0-15%) of the subjects in the three groups consistently hold an alternative conception as compared to the results in Table 5 which shows responses for individual items. For example, only 1% to 2% of the subjects in the three groups consistently had the alternative conception that a more reactive ion displaces a less reactive one in complex salt formation. In general, the secondary students had a higher percentage of consistent alternative conceptions compared to the more advanced chemistry subjects. The consistent alternative conception most widely held (23%) by the secondary students was that a new solid was formed when an acid was added to a mixture of a complex salt and excess alkali. However it should be noted that between 9% to 10% of the advanced chemistry subjects also consistently held the same alternative conception, indicating that additional learning does not totally remove this alternative conception. Other persistent alternative conceptions were that acid removed the solvent for the precipitate (item 2 under 'Dissolution' in Table 6) and that needed to acidify a mixture so that reaction could proceed properly. As mentioned previously, this showed that, even with additional chemistry learning, a number of subjects did not understand the common procedure of adding dilute acid to a mixture containing a complex salt, or when silver or lead (II) solutions were used to identify anions. This might indicate the students carried out qualitative analysis mechanically, without understanding, and supports a good argument for a closer examination of how qualitative analysis is taught at the various educational levels.

The lack of consistency of alternative conceptions held by the subjects could point to them having more than one conception for a particular concept and "different conceptions can be brought into play in response to different problem contexts" (Palmer, 1999, p. 639). Palmer proposes that his "personal propositions" (p. 649) model provides an explanation for students' inconsistencies in science and the prevalence of such inconsistencies even right through tertiary level. He believes that the student has a collection of scientific concepts and alternative conceptions and that the student's knowledge structures or personal propositions guide the student on which to use in any given situation. He contends that there is no inconsistency from the viewpoint of the student because the responses will be "a true reflection of the 'if…then' nature of their understanding" (p. 650). Using a diagnostic instrument on ionisation energy, Taber (1999) also found that "apparently related items do not always receive a consistent level of support from the students" (p. 103). He holds similar beliefs as Palmer that students "may have several alternative explanatory schemes that can be applied to a particular context" (p. 103). The study by Voska and Heikkinen (2000) on student conceptions in chemical equilibrium also revealed that only a small proportion of students showed consistency in their thinking. Finally, the lack of consistency could also be due to students not having adequate understanding of the topic and resorting to guessing.

There also was no predictable pattern in the consistency of the alternative conceptions with respect to increasing educational level and this could indicate that the alternative conceptions were retained even with increasing chemical education. The findings of this study are supported by the results of a similar cross-age study by Birk and Kurtz (1999), using the two-tier diagnostic instrument developed by Peterson and Treagust (1989), on the effect of experience on the retention and elimination of alternative conceptions on molecular structure and bonding.

Implications

This cross-age study showed that, in general, all levels of subjects did not perform well on the QADI. Though the graduate group (mean score 52%) performed significantly better than the junior college (43%) and secondary students (30%), it was worrying that many of the would-be teachers and in-service teachers did not have adequate conceptual understanding of the basic QA concepts and reactions measured by the QADI. Thus, it is likely that their own students will find difficult to understand QA – how does one teach for understanding when one does not have an adequate conceptual understanding in the first instance?

Many of the alternative conceptions were prevalent among the different groups indicating that they were "robust enough to have survived schooling" (Palmer, 1999, p. 648). However, these alternative conceptions were consistently held by only a small number of subjects (0-23%) across all contexts examined in the QADI, indicating that the subjects might have more than one conception for a particular concept or had little understanding of qualitative analysis and resorted to guesswork. Additional evidence of students' lack of understanding of QA was obtained from interviews with 51 Grade 10 students (Tan et al., in press). Twenty-six students admitted that they had little idea about what they were doing during QA practical sessions. They often did not know why they were instructed to use a certain reagent, what they were testing for, what reactions occurred, or why they obtained a particular result.

The author believes that the main reason for students' lack of understanding of QA is the requirements of the present O-level QA practical examinations - students are assessed only on their written reports and the bulk of the marks are allocated to correct observations. Thus, they can do very well just by writing all the correct observations. The lack of emphasis on understanding leads to a situation where teachers tend to concentrate more on 'drill and practice', doing past years' examination questions and writing 'model' answers than on enhancing students' thinking and understanding. The following comments of a teacher highlight the focus of QA lessons:

> I only gear them towards observations because the O-levels only require them to write the correct observations…so I gear them towards recording the correct observations, how to carry out the tests, how to get marks from the report…so I'm very focussed…I don't have time to explain every detail…what reaction is taking place.

Thus, the nature of examinations has significant impact on implemented curriculum (Hodson, 1993). To encourage more meaningful learning of QA, the present system of assessment needs to be expanded to include the assessment of manipulative and planning skills, as well as the understanding of the concepts involved in QA. Indeed, these are the focus of the new practical assessment system which will be implemented in 2004/5. Making these changes could lessen the need for 'drill and practice', and encourage teachers to provide the appropriate experiences for the meaningful learning of qualitative analysis.

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Appendix: Examples of items in the QADI

For Questions 1 to 4, refer to Experiment A:

Experiment A

Step	Test	Observations
a	To a sample of aqueous zinc chloride, add aqueous sodium hydroxide until a change is seen.	*A white solid is obtained.*
b	Add excess of aqueous sodium hydroxide to the mixture from (a).	*White solid disappears in excess reagent to give a colourless solution.*
c	Add dilute nitric(V) acid (HNO_3) to the mixture from (b) until no further change is seen.	*White solid reappears. When excess acid is added, the solid disappears giving a colourless solution.*

1. What happens when aqueous sodium hydroxide is added to aqueous zinc chloride resulting in the white solid?

A Displacement

B Precipitation

C Redox

Reason/Justification

1. The solution is too concentrated with sodium chloride so the sodium chloride comes out of the solution as a solid.
2. Sodium hydroxide loses oxygen in forming sodium chloride and zinc chloride gains oxygen in forming zinc hydroxide.
3. Sodium ion is more reactive than zinc ion.
4. Zinc ions combine with the hydroxide ions.

2. In step (b), a colourless solution is obtained because the white solid _____ the excess sodium hydroxide.

A dissolves in B reacts with

Reason/Justification

1. More solvent is added so there is more space for the white solid to dissolve.
2. No further reaction is seen except for the disappearance of the white solid, and no new reagent is added.
3. Sodium ion displaces the cation from the white solid.
4. The white solid forms a new soluble compound with the excess sodium hydroxide.

3. A student concludes that the white solid observed in step (c) is the same as the white solid obtained in step (a). Do you agree with the student's conclusion?

A Yes B No

Reason/Justification

1. Different reagents were used.
2. The acid reacts with the excess sodium hydroxide to form sodium nitrate(V) which appears as the white solid.
3. The acid reacts with the zinc compound to form zinc nitrate(V) which appears as the white solid.
4. The acid reacts with the mixture to reverse the formation of the soluble compound in step (b).
5. The acid removes the solvent which dissolves the white solid in step (b), so the white solid reappears.

4. The student also concludes that, in step (c), the white solid dissolves because more solvent (dilute nitric(V) acid) is added. Do you agree with the student's conclusion?

A Yes B No

Reason/Justification

1. Adding more acid dilutes the solution.
2. Hydrogen is more reactive than the cation in the white solid, so it displaces the cation from the solid.
3. No further reaction is seen except for the disappearance of the white solid, and no new reagent is added.
4. The acid contains hydrogen ions which reduce the white solid.
5. The acid reacts with the white solid to form a soluble compound.

TABLE 1

Descriptive Statistics for the Three Educational Level Groups to whom the QADI was administered

	Sec 4	JC	G

No. of cases	915	360	98
No. of items	19	19	19
Cronbach alpha reliability	.68	.72	.81
Mean (Standard deviation)	5.8 (3.3)	8.1 (3.7)	9.9 (4.4)
Median / Mode	5.0 / 5	8.0 / 9	6.0 / 6
Minimum / Maximum	0 / 18	1 / 18	1 / 19

Note: Sec 4 - group of Grade 10 students

JC - group of junior college students

G - group of graduate trainee-teachers and in-service teachers

TABLE 2

Comparison of the Different Educational Level Groups for Mean Scores on the QADI using an Analysis of Variance

	Sum of Squares	df	Mean Square	F value	p value
Between Groups	2542.44	2	1271.22	104.92	<.001
Within Groups	16599.83	1370	12.12		
Total	19142.27	1312			

TABLE 3

Post Hoc Pairwise Multiple Comparisons (Tamhane) of Mean Scores on the QADI for the Three Educational Level Groups

Pairwise groups		Mean Difference (Std. Error)
G	JC	1.75* (.40)
G	Sec 4	4.12**(.37)
JC	G	-1.75*(.40)
JC	Sec4	2.37**(.22)

Sec 4	G	-4.12**(.37)
Sec 4	JC	-2.37**(.22)

Note: * $p < 0.01$

** $p < 0.001$

TABLE 4

The percentage (20% or more) of secondary students / junior college students / graduates selecting response combination for each item in the QADI

Item	Content option	Reason option				
		(1)	(2)	(3)	(4)	(5)
1	A	~	~	*25/~/~*	~	-
	B	~	~	~	**41/68/67**	-
	C	~	~	~	~	-
2	A	*29/~/~*	~	~	26/39/25	-
	B	~	~	~	**19/30/49**	-
3	A	~	~	~	**17/46/46**	*~/26/~*
	B	*24/~/~*	~	~	~	~
4	A	~	~	~	~	30/30/29
	B	~	~	~	~	**22/27/38**
5	A	*20/~/~*	**43/52/67**	~	*~/21/~*	-
	B	~	~	~	~	-
	C	~	~	~	~	-
6	A	~	~	~	~	*22/22/~*
	B	~	**34/39/30**	~	~	~
	C	~	~	~	~	~
7	A	~	~	~	~	~
	B	~	**48/61/72**	~	~	~
8	A	*41/34/33*	~	~	~	-
	B	~	~	~	**20/37/41**	-
9	A	~	~	~	~	~
	B	~	~	**19/41/58**	~	~
		23/27/~	~	~	**35/43/40**	-

10	A B	~	~	*27/~/34*	~	-
11	A B	~ ~	**24/17/44** ~	~ *20/24/~*	~ *25/33/~*	~
12	A B	*26/22/26* ~	~ **38/44/49**	~ ~	*20/26/~*	- -
13	A B C	~ ~ ~	~ **45/61/64** ~	~ ~ ~	~ ~ ~	- - -
14	A B	~ ~	*25/~/~* ~	~ ~	~ **29/48/57**	- -
15	A B	~ ~	~ ~	**23/50/55** ~	*~/25/21* ~	- -
16	A B	~ ~	~ ~	~ ~	~ ~	~ **23/31/48**
17	A B	~ ~	~ ~	~ ~	*35/38/33* ~	~ **20/25/28**
18	A B	~ ~	~ ~	~ **48/56/74**	~ ~	~ ~
19	A B	~ *26/21/~*	~ ~	~ **29/39/62**	~ ~	*21/22/~*

Note: ~ represents less than 20%

Figures in italics represent alternative conceptions

Figures in bold represent the correct answer

TABLE 5 Alternative conceptions of the three educational levels of students

Alternative conception	Choice combination	Percentage of students with the alternative conception		
		Sec 4	JC	G
Displacement		25		
1. A more reactive ion displaces a less	Q1 (A3)	37	~	~

reactive ion in a double decomposition/ precipitation reaction.	Q5 (A1,A4) Q18 (A1,A2, A4&A5)	29	35 21	26 ~
Dissolution 1. A precipitate is formed when a reagent is added to an unknown solution. On further addition of excess reagent, the precipitate disappears because more excess reagent means more space/volume for the precipitate to dissolve. 2. Ammonium chloride is formed when aqueous ammonia is added to silver chloride because it is a soluble salt. 3. When acid is added to a mixture containing excess alkali and a complex salt it removes the solvent (alkali) for the precipitate.	Q2 (A1) Q14 (A2) .Q8 (A1) Q3 (A5) Q15 (A4)	29 25 41 ~ ~	~ ~ 34 26 25	~ ~ 33 ~ 21
Addition of acid 1. Acid is needed to acidify the mixture so that reaction can proceed properly. 2. Any acid can be used because acids have the same properties and reactions. 3. Carbonate ions cannot be determined if acid is added after the addition of barium nitrate (V). a. The acid must be added directly to the unknown. b. The procedure is strictly a test for sulphate (VI). 1. When acid is added to a mixture of a complex salt and excess alkali, a different solid from the original precipitate is formed.	Q6 (A5) Q17 (A4) Q12 (A1) Q11 (B4) Q12 (B4) Q11 (B3) Q3 (B1,B2 & B3) Q15 (B1& B2)	22 35 26 25 20 20 52 29	22 38 22 33 26 24 21 ~	~ 33 26 ~ ~ ~ 20 ~
Heating 1. All gases have to be tested when a substance is heated. 2. Oxygen cannot be produced when a substance is heated because it is used up during heating. 3. Compounds containing hydrogen and hydroxide ions will liberate hydrogen on heating. 4. Ionic compounds have strong bonds and do not decompose on heating.	Q10 (A1) Q10 (B3) Q19 (A5) Q19 (B1)	23 27 21 26	27 ~ 22 21	~ 34 ~ ~

Note: ~ represents a figure which is less than 20%

Table 6

Consistent alternative conceptions of the three educational levels of students

Alternative conception	Percentage of students with the alternative conception		
	Sec 4	JC	G
Displacement			
1. A more reactive ion displaces a less reactive ion in a double decomposition/precipitation reaction.	11	5	6
2. A more reactive ion displaces a less reactive ion in complex salt formation.	1	1	2
Dissolution			
1. A precipitate is formed when a reagent is added to an unknown solution. On further addition of excess reagent, the precipitate disappears.			
a. More excess reagent means more space/volume for the precipitate to dissolve.	4	1	2
b. The precipitate is considered to have dissolved in the excess reagent as no further reaction is seen and no new reagent is added.	8	5	3
1. When acid is added to a mixture containing excess alkali and a complex salt it removes the solvent (alkali) for the precipitate.	9	15	12
Addition of acid			
1. Acid is needed to acidify the mixture so that reaction can proceed properly.	14	14	10
2. Any acid can be used because acids have the same properties and reactions.	8	7	4
3. Dilute nitric (V) acid is added to acidify mixtures because it is a strong oxidising agent.	3	1	
4. Carbonate ions cannot be determined if acid is added after the addition of			

barium nitrate (V) as the acid must be added directly to the unknown. 5. When acid is added to a mixture of a complex salt and excess alkali, a different solid from the original precipitate is formed.	10 23	14 9	9 5 10