Representation of demostrated reactions: imagery (macroscopic) or schematic (symbolic)

Representación de experimentos químicos demostrados: con imagen (macroscópico) o con esquema (simbólico)

Denis M. Zhilin

Moscow Institute for Open Education,
zhila2000 @mail.ru

Abstract

The performance in completing equations (writing products for given reactants) and descriptions of observed reactions were compared. The participants were 14-15 yearold pupils of accelerated classes in Russia. It was shown that after half a year study period when they were exposed to demonstrations, the participants (a) complete equations much better than they describe reactions, (b) complete equations before writing descriptions and (c) use equations to reconstruct descriptions but almost never vice versa. One week after a demonstration, pupils can complete almost all equations, but forget the observable effects except the most impressive ones. It means that reactions are represented in the long-term memory as schemas rather than as images. Image representation (if present) is weakly connected with the schematic one because pupils often attribute the effects to wrong reactants.

Keywords: *chemical demonstrations, cognitive mechanisms, chemical equations, chemical reactions, long-term memory*

Resumen

Durante los experimentos se comprobaron los resultados de las reacciones químicas (descripción de los productos reactivos dados) y la descripción de las reacciones observadas, a los participantes del experimento, preliminarmente. En el experimento participaron alumnos de educacion media (14-15 años) rusa especializados en química y biología. Se concluye que 1) después de seis meses de enseñanza durante la cual los alumnos observaron las reacciones químicas, los participantes: (a) terminaron las ecuaciones químicas mucho mejor que la descripción de las reacciones; (b) terminaron las ecuaciones químicas antes de describirlas; (c) aprovecharon las ecuaciones químicas para reconstituir sus descripciones pero, casi nunca se hizo lo contrario; 2) los alumnos pudieran terminar las ecuaciones químicas una semana después de la presentación, pero, olvidaron efectos exteriores, excepto, los más impresionantes. Esto significa que las ecuaciones químicas se almacenan en la memoria a largo plazo en forma de esquemas pero no, como imágenes.

Palabras clave: *demostraciones químicas, mecanismo cognitivo, ecuaciones químicas, reacciones químicas, memoria a largo plazo*

INTRODUCTION

One of the main purposes of chemistry is to predict the products and effects of chemical reactions; hence, this is one of the goals of teaching advanced chemistry. As long as products are described by chemical equations, the skills of completing equations (namely, writing products with given reactants) are very important for advanced chemistry students. In Russia these skills are required by the Federal Educational Standard. The question is: whether chemical demonstrations help to teach completing chemical equations and, if yes, how they do it.

The role and effectiveness of demonstrations

The necessity of demonstrations in teaching chemistry is a matter of total acceptance. Bent & Bent (1980) cited dozens of quotations in favour of chemical experiments. Numerous books and articles are published, where hundreds of demonstrations are described (for example, Shakhashiri, 1983-1992; Lister, 1995 etc). However, if one asks the question "How demonstrations affect learning chemistry and do they really have any effect" one would hardly find an evidence-based answer. There are many arguments that could be divided into two groups (according to Wellington, 1998): cognitive (improving the pupil's understanding) and affective (generating interest and enthusiasm). For example: "reinforcement of learning by visualizing abstract scientific concepts", "linking senses with positive emotion imaginary" (Shimaefsky, 2004, p. ix), "sparking student interest, initiating scientific inquiry, and displaying scientific phenomena" (Swanson, 1999). However, no substantiation is provided. Most of recommendations of how to conduct demonstrations (Shakhashiri, 1989; Bent & Bent, 1980; O'Brien, 1991) seem reasonable in general. Nobody would argue that demonstrations must be timely and appropriate; well-prepared and rehearsed; visible and large-scale; simple and uncluttered; direct and lively; dramatic and striking (Shakhashiri, 1989, p.15-16). But all the recommendations are intuitive rather than evidence-based. This means that they allow a number of alternative interpretations. For example, where are the borders between simple and complex, dramatic and dull, direct and indirect?

The evidence-based investigations of demonstration effectiveness (rather for "conceptual understanding" than for skills to complete equations) are summarized by Majerich & Schmuckler (2008). A comparison of laboratory training and demonstrations had shown inconclusive results – neither of the methods proved to be superior. However, lectures with demonstrations (especially accompanied by discussions) give better results than lectures without demonstrations (Knox, 1936). Later findings (Erlis and Subramanian, 2004 and Raid 2009) confirmed these results for concept-based and topic-based tests, but not for completing equations. The positive effect of demonstrations summarized by Tsaparlis (2009) also deals with concept understanding but not completing equations.

Researchers have also reported failures of learning from demonstrations. Some of them occur when minor but striking outcomes divert students' attention from the essential ones (Kiryushkin & Polosin, 1970; Tsaparlis, 2009 and refs.), especially when students do not know what to focus on (Roth et al., 1997). The other reasons (enumerated ibid) could be summarized as incompatibility of student's and teacher's discourses. One more reason is a mismatch between the pace of demonstration and its perception. It is indirectly confirmed by Eniaiyeju (1983), who has shown the benefits of self-paced programs. All these reasons cause inattentional blindness ("looking without seeing", Mack, 2003): people tend not to perceive unexpected events. As a result, students "remembered not what they saw but what they expected to see" or "students retained a memory of the outcome of the demonstrations that did not occur" (Majerich & Schmuckler, 2008 and references therein).

Demonstrations and representations

These examples show the role of cognitive mechanisms in the effectiveness of demonstration. However, very few authors investigated this issue. Beasley (1982) reported an increased level of pupil attention and task involvement in demonstrations employed in a high school setting. In a study of an introductory college physics course, Buncick et al. (2001) organized demonstrations to promote active engagement among students. It could even be a catalyst for student initiated inquiry as well as a learning opportunity since it helps to create mental links between previous and new learning (Meyer et al., 2003). The authors further add that students can model cognitive strategies by observing the teacher's thinking aloud as s/he conducts the demonstration and how he frames questions that lead to explanations of the underlying concepts. This could challenge students' existing understanding and hopefully foster conceptual understanding (Shepardson et al., 1994). The clearest cognitive mechanism is cognitive conflict (Bodner, 2001), which was successfully used by Zimrot & Ashkinazi (2007) and Baddock & Bucat (2008). However, to organise a cognitive conflict, a lecturer should use a prediction-observation-explanation strategy (White, Gunstone, 1992). Very often students cannot predict any effect of reaction and this strategy fails.

All of the cited results deal with the perception or interpretation of information. Meanwhile, other important parts of information proceeding are storage and recollection (Reid, 2008). This is a matter of representation.

Within the framework of "chalk chemistry" chemical reactions can be represented only by equations. In terms of chemistry teaching, it is symbolic representation (Johnstone, 2006; Gilbert & Teagust, 2009) that is taken for granted by 'experts' (i.e. chemists, science teachers etc.) but may not always be well understood by students even at the university level (Taber, 2009 and refs.) In terms of cognitive psychology, it is schematic representation or propositions (Clark, Paivio, 1991; Sternberg, Sternberg, 2009). Here we can regard chemical equation as a kind of statement in a formal language (Taber, 2009; Laszlo, 2011) with reactants as a verbal stimulus and products as the verbal response.

While demonstrating chemical reactions with corresponding explanations, another type of representation emerges. In terms of cognitive psychology, it is visual representation, and in terms of chemistry teaching, it is the macroscopic or phenomenological representation.

The term "representation" here is ambiguous. From the teachers' point of view, it is a mode of presentation of objects to students or by students and could be regarded as external. This is obvious, for example, from the interpretation of students' interviews taken by Hinton & Nakhleh (1999). From the cognitivists' point of view, representation is a way of storage of information in mind and could be regarded as internal. However, in the case of chemical reaction, there is a correspondence between "external" and "internal" representation. We could state that information presented in the symbolic mode is stored as schemas, whereas that presented visually is stored as mental images (the latter coincides with functional-equivalence hypothesis, Sternberg, Sternberg, 2009 and refs.).

The main question is interrelations between these two pairs of representations. On the one hand, we use visual images to solve problems and to answer questions involving objects (Kosslyn & Rabin, 1999; Kosslyn, Thompson & Ganis, 2006). On the other hand, educational researches on connections between symbolic and microscopic levels show weak interrelations between them and importance of enhancing these interrelations (Gabel, 1998; Roehrig & Garrow, 2007). Students also tend to confuse the levels (Chandrasegaran, 2008). Cognitive theories (such as Dual Coding Theory) also state a distinction between verbal and imagery systems (Paivio, 2006) whereas cognition is interplay between these two systems.

Working hypothesis

Thus demonstration accompanied by explanations could combine macroscopic and symbolic (in teaching terms) or visual and schematic (in cognitive terms) representations helping to complete equations. Whether it really does so? If yes, what is primary and what is secondary? Do pupils use the visual images of reactions they observe to complete their equations?

Following cognitive theories the answer could be positive because the necessary information can be extracted by recalling and scanning the image (Denis, Kosslyn, 1999). Teaching practice also suggests a positive answer. Majerich, (2004) states that "the students were better able to recall science demonstrations than activate the science knowledge learned from the demonstrations". Bent & Bent (1980) give a lot of quotations underlining the excitement of demonstrations and its role for personal experience. Shimaefsky (2004) states that students keep facts and concepts in their minds longer when the information presented to them is enlivening and easy to recall. Zimrot & Ashkenazi (2007) showed that students remembered the outcome of experiment better than they underwent conceptual change.

So, the working hypothesis is as follows: students store visual images of chemical reactions that are connected with products of reactions. Recalling these images facilitates completing of equations. Then the research question is whether visual images are stored in the long-term memory and whether they help to complete equations.

To answer this question, we demonstrated a number of chemical reactions with the corresponding equations to 14-15 year old pupils. They recorded their observations and the equations. After a period of time, they were asked to complete the equations of some reactions they observed (symbolic level) and describe their observations (macroscopic level). The performance in description and completing the equation was compared.

Experimental

Participants

There were four groups of participants (Table 1). All the participants were pupils of accelerated classes (School #192, Moscow, Russia). They had been studying chemistry since the 7th grade having 4 hours a week in the 7th grade and 5 hours in the 8th and 9th grades.

Table 1 Main features of the conducted experiments

Group	Grade (Age) of participants	No. of participants	No. of reactions	Total No. of answers
A1	9 (15)	20	8	160
A2	9 (15)	17	10	170
A3	8 (14)	19	10	190
B1	8 (14)	11	5	55

The experiment was conducted within the regular curriculum that included inorganic chemistry lessons once a week. In these lessons, the teacher (the author of this article) demonstrated different reactions. The observations were discussed to point out all the outcomes that could be connected with the products. The participants recorded observations and discussed with relation to the products. Then the teacher wrote the equation on the blackboard and made sure that pupils recorded it.

Apart from these lessons, the pupils were taught basic chemical concepts and trained general skills of completing equations based on the classification of reactants.

Experimental Design

The first three groups (groups A1-A3) were exposed to demonstrations for half a year. After half a year, they took a test. They were given reagents and asked to describe reactions between them and complete the corresponding equations. All the reactions had been demonstrated within the previous half a year. The set of reactions varied from group to group, because the demonstrated reactions also had varied. The number of reactions in the test is given in Table 1.

The fourth group (B1) was asked to describe reactions and complete equations a week after these reactions were demonstrated. We also compared the results of this group with their records at the demonstration lesson.

An example of a task is as follows: "complete equation $S + O_2 \rightarrow \ldots$ and describe the observed effects in any order". The expected answer: "Sulphur melts and burns with dim blue light and gives gaseous choking products; $S + O_2 \rightarrow SO_2$".

The test stage for both schemes lasted for 40 minutes and was arranged as an ordinary school test. The participants were not aware of it, so they did not prepare deliberately. After the test stage all the participants said that it was enough time for them to do everything they could.

Data Analysis

The equation and the description of one reaction given by one participant is referred to as an answer (Table 2).

Each answer got two marks: one for the description and one for the equation. If the description included all the key features, it got 1 point. If the description contained only a part of the key features, it got 0.5 point. If all the features in the description were wrong or absent, it got 0 points. The mark for the equation was 1 if all the reactants and products were mentioned, 0.5 if some of the products were missed, and the mark was 0 if there were no correct products. When two equations were possible (either corresponding or not corresponding to the observations but present in textbooks), either of them got 1 point.

The normality (Shapiro-Wilk criterion) and 0-hypothesis were tested in the Origin 7.5 program (OriginLab corporation).

RESULTS

Recalling descriptions and equations after long-term study

First of all, we calculated the percentage of correct (score 1) and partly correct (score 0.5) answers in groups A1-A3 that were exposed to demonstrations for half a year. Comparing the results (Table 2), one can see that the participants complete equations much better than they describe reactions. Moreover, if they complete an equation, they do it correctly as a rule. However when describing reactions, they often forget some of its key features. Ten participants even did not try to describe reactions (saying that they "don't remember anything") but completed some equations.

Table 2 Percentage of correct or partly correct answers

Group	Correct (score = 1)		Partly correct (score = 0.5)	
	Description	Equation	Description	Equation
A1	14	46	13	12
A2	8	25	5	12
A3	12	43	13	21

Even this preliminary treatment refutes our working hypothesis – the images of reactions cannot help to complete equation because the pupils cannot recall images even if they complete an equation.

To find out whether the performance in descriptions is connected with the performance in equations, we calculated correlations between the sum of scores for descriptions and for equations got by each participant (Table 3). However, the results turned out to be inconclusive, which is not surprising for such small samples. The distribution of descriptions was not normal in two of the three groups, which hampers the correlation analysis. However, particularly for these groups, the correlation was significant.

Table 3 Correlations between the scores in equations and descriptions (p=0.05)

Group	Normality of distribution		R^2	Significance
	Descriptions	Equations		
A1	Yes	Yes	0.14	No
A2	No	Yes	0.49	Yes
A3	No	Yes	0.33	Yes

To obtain conclusive results, we compared scores for equations and descriptions for each answer. When the score for a description was higher than the score for the equation, we considered that the description is better than the equation and vice versa. When both scores were 0, we considered the description and the equation to be equally unsuccessful. When both scores were 0.5 or 1 (description and equation were correct or partly correct), the description and the equation were considered to be equally successful. The results for A1-A3 groups are presented in Fig. 1

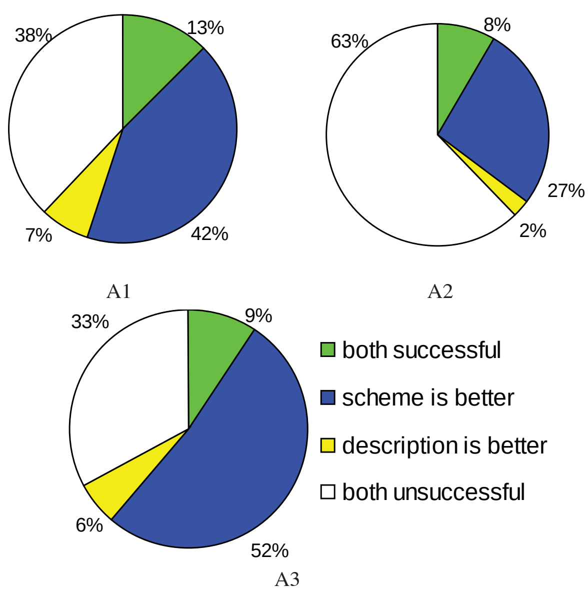

Fig. 1. Comparing the outcomes of recalling description of a reaction and its equation (percentage of answers).

It is obvious that the number of answers with better equations drastically exceeds the reverse. It also exceeds the number of equally successful answers (i.e. answers with both marks 0.5 or 1). This pattern is reproduced from group to group, meaning that it does not depend on (a) particular group or (b) particular set of reactions. This means that it was not necessary to establish the formal equivalence of groups of participants as well as sets of reactions – the pattern is the same even if they are not equivalent. There is also no significant gender difference (on t-criterion based on three groups).

The vast majority of participants revealed the same individual pattern: only one participant had better score for description (1.5 points against 0.5 that is too low) and 4 participants got equal scores more than 1 point (2 twice, 3.5 and 7). Other participants got better overall scores for equations. Moreover, the vast majority of participants (35 against 1) who wrote the descriptions did this after the equations. This means that equation is the primary thing to be recalled.

All these facts show that imagery (macroscopic) representations do not help pupils to conclude chemical equations. Images of reactions observed long ago are seldom stored in pupils' minds. However, schematic representation of chemical reactions (namely, their equations) sometimes helps participants to describe reactions, maybe even without recalling their images.

This is confirmed by some particular answers. First, there were nine answers where pupils wrote descriptions that matched the wrong equations they offered. For example, while completing the equation of thermal decomposition of basic copper carbonate "$(CuOH)_2CO_3 \xrightarrow{t^\circ}$ ...", one participant indicated $Cu(OH)_2\downarrow$ as a product and, according to its colour, reported "blue precipitate" in the description, whereas the observed product was black CuO. However, only one answer contained a description that did not match the equation. In one case (burning of copper in chlorine), the correct equation was given, but the description of the product ($CuCl_2$) was irrelevant to that particular reaction (when the substance is anhydrous and therefore yellow-brown) but was relevant to much more common and familiar situation (when this compound is hydrated and therefore green). All these particular answers mean that symbolic representation (equations) serve as scaffolds in reconstructing macroscopic representations of chemical reactions that are not represented in pupils' mind as images.

However, sometimes (very seldom) pupils do store images. This is confirmed by two answers with correct description without any equation in conjunction with descriptions that are better than equations (Fig. 1). One participant definitely used images to reconstruct schematic representation, because he wrote descriptions before equations and wrote two equations matching incorrectly the recalled images. For example, he described the process $Pb + KNO_3 \xrightarrow{t^\circ}$ as "the reactants melt, then give off a brown gas and a yellow product" (that is similar to decomposition of $Pb(NO_3)_2$ he also observed) and wrote PbO and NO_2 (brown gas) among the products. However, this is relevant to very few pupils – the majority of them seem to use equations to reconstruct descriptions.

Recalling descriptions and equations of particular number of reactions

To prove the idea that chemical reactions are represented in the long-term memory rather as schemas than as images, we checked how pupils of group B1 forget their observations in comparison with equations. We demonstrated a set of eight reactions and after a week, tested how they remembered five of them. The results are shown in Table 4. Three reactions that were demonstrated but not tested were reactions of sodium, lithium and burning magnesium with water. We did not include them in the test because their equations are quite similar to those presented in the test and this could have increased the number of equations completed by analogy rather than using images of reactions.

Table 4 The record of essential effects and products by B1 group

Reaction	Total number of		Average reported portion of correct effects, %			Average reported portion of products, %		
	effects	products	Immediately after	After a week	Forgotten after a week	Immediately after	After a week	Forgotten after a week
$K + H_2O$	6	2	47	32	32	100	91	9
$Ca + H_2O$	4	2	96	16	83	100	77	23
$P_2O_5 + H_2O$	3	1	94	39	58	82	45	44
$CaO + H_2O$	1	1	91	9	90	82	82	0
$SOCl_2 + H_2O$	5	2	67	13	81	100	64	36

Straight after the lesson with demonstrations the pupils recorded almost all the effects (at least if there was 4 or less of them for one reaction). They also recorded almost all equations (except six by three pupils).

After a week, the participants completed the majority of equations, but had forgotten almost all of the effects they recorded. 22 answers out of 55 contained no correct description, the others contained very small number of effects. The only exception was reaction of potassium with water, which has very bright effects (burning, sparkling and so on, Fig. 2). It confirms that pupils do not remember images if they are not extremely bright. Image representations of other reactions rarely remain in their minds after a week.

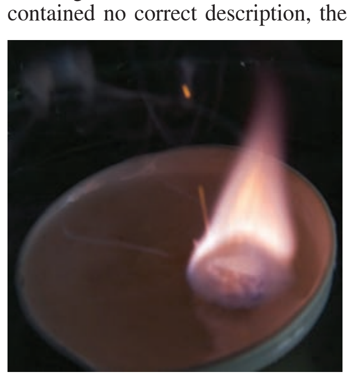

Fig. 2. Reaction of potassium with water – the brightest reaction demonstrated to B1 group.

Pupils of B1 group made many remarkable mistakes (22 answers out of 55) that were almost not observed for A1-A3 groups. They confused observations for different reactions, replacing less bright by more bright (or adding effects from more bright), but not *vice versa*! Eighteen answers described reaction of Ca, CaO or P_2O_5 with water (accompanied by warming-up and sometimes gas production) as the reaction of sodium or burning magnesium (with sparks, flame and so on), but nobody described reaction of potassium with water as reaction of Ca, CaO or P_2O_5. This means that images of spectacular reactions are represented in minds that can be easily explained by their emotional impact (Hamann, 2001). However they are not associated with particular reactants and thus cannot serve as scaffolds in completing equations. One can say that they are components of episodic memory rather than of semantic. Another possible interpretation is that image representation is only weakly connected with schematic.

DISCUSSION

The results show that chemical reactions are represented in pupils' mind predominantly as schemas. We don't know whether pupils store complete equations or just possess a procedural knowledge how to complete equations deducing products from reactants, but the image representation of reactions does not help them to complete equations. Moreover, they store image representations very seldom and often with no connection to a particular reactants. The opposite situation, namely, reconstructing descriptions basing on equations, is encountered much more frequently but not always.

These results seem to contradict the findings of Pekdag & Le Marechal (2007), who investigated memorization of chemical movies. They have found that after 7 days, students remembered more pictures of the movie than words of the narration, and from the picture, they remember more icons than animations or photos, and almost no symbols. This difference could be explained (a) by special attention that was paid by the teacher to writing equations along with demonstrations in our experiment and (b) by "inattentional blindness" towards symbols in movies. We could also suggest that recording equations distorts pupils from recalling images. It coincides with early findings of Carmichael et al. (1932) that labels for figures distort the recalling of visual images (if consider equations as labels).

Our conclusions are counterintuitive, but it could be explained by means of cognitive science (Sweller, 2003; Reid, 2008). According to the cognitive science, the information in long-term memory is stored as schemas (semantic or procedural). Equations are kinds of schemas, so they fit the cognitive architecture of humans, while images do not fit. Schematic representation turns out to be less consuming than imagery.

The common failure of reconstructing descriptions based on completed equations shows that the problem of connecting symbolic level of representation with macroscopic is extremely difficult. Our approach was not absolutely successful for it. It is not enough just to show a reaction and the links between its products and effects.

The rejection of our working hypothesis retains the question of how demonstrations affect the skills of completing chemical equations. This is a matter for further investigations.

Limitations of the study

The experiment was conducted with highly motivated pupils 14-15 y.o. with high academic performance, who can be regard as experts at least among their peers. One should be very careful with extension of the results to less motivated pupils, novices in chemistry or students of other ages.

The way of connecting effects with equations also can influence the results. Another mode of demonstration could form imagery representations much more effectively than in ours.

CONCLUSIONS

1. The vast majority of pupils better complete equations of reactions than describe them.
2. Chemical reactions are represented in the pupils' minds rather as schemes than as images.
3. Equations of chemical reactions sometimes help pupils to reconstruct description. The opposite situation is seldom.
4. If chemical reaction is represented as image, it is rarely connected with schematic representation (namely, with the reactants).

Educational consequences

The conclusions have at least two consequences for teaching chemistry.

1. When a pupil cannot deduce products of reaction that he has seen, it is useless to recall its image – there is no image in pupil's mind.
2. When employing demonstrations for teaching pupils to predict products of reactions, one should pay a particular attention to connecting the macroscopic and symbolic levels of representation during demonstrations. Otherwise, the images and equations of reactions would be stored unlinked and would not help each other.

Our research also shows that some intuitive ideas about chemical demonstrations and their role in chemistry teaching could turn out to be wrong. Thus all the intuitive ideas should be checked experimentally.

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Critical thinking. Can it be measured?

Pensamiento crítico. Se puede medir?

Khalid Hamoud Alosaimi [1], Norman Reid [1], Susan Rodrigues [2]

[1] Universities of Dundee and Glasgow, Scotland, UK, [2] Escieducation.Ltd, UK
E-mail: dr_n@btinternet.com

Abstract

It has been argued that critical thinking is a vital skill in science education. However, there is a lack of clarity in describing what is meant by critical thinking and no test designed to measure this skill. This paper seeks to develop an operational description of critical thinking. Using that description, a test of critical thinking was developed for 13-15 year old school students. After several stages of scrutiny and a pilot study, the test was used with a sample of 240 school students from Saudi Arabia across three age groups. The outcomes from the test were related to measured working memory capacity and to performance in science examinations. The findings show that, while critical thinking has to take place in the working memory, the test outcomes were not being controlled by the capacity of working memory. It also showed that the test of critical thinking, although based largely on science content, was not a measure of that content.

Keywords: c*ritical thinking, working memory capacity, science performance*

Resumen

Se ha sostenido que el pensamiento crítico es una habilidad vital en la educación científica. Sin embargo, hay una falta de claridad en la descripción de lo que significa el pensamiento crítico y hay una prueba diseñada para medir esta habilidad. Este trabajo busca desarrollar una descripción operacional del pensamiento crítico. Con esa descripción, una prueba de pensamiento crítico fue desarrollado para estudiantes de 13 a 15 años de la vieja escuela. Después de varias etapas de control y un estudio piloto, la prueba utilizó una muestra de 240 estudiantes de las escuelas de Arabia Saudita a través de tres grupos por edad. Los resultados de la prueba se relacionaron con medidas de capacidad de memoria de trabajo y el desempeño en los exámenes de ciencias. Los resultados muestran que, mientras que el pensamiento crítico debe tener lugar en la memoria de trabajo, los resultados de las pruebas no fueron controlados por la capacidad de esta memoria . También demostró que la prueba de pensamiento crítico, aunque se basa en gran medida en el contenido de la ciencia, no era una medida de ese contenido.

Palabras clave: *pensamiento crítico, capacidad de memoria, rendimiento en ciencias*

INTRODUCTION

There has been exponentially rapid progress in science and technology in recent years. Access to knowledge has changed dramatically with new technologies. The value of what we know is being eroded and replaced step-by-step by an increasing value placed upon a knowledge of how to obtain information. In turn, this generates an increasing need to know what knowledge to seek and how to evaluate what is found. Thus, educational development requires a new outlook on the way students think: this does not mean changing what they learn, but it does mean changing how they think.

In this context, the concept of critical thinking has gained in importance and has become a widely-used term in the education field in recent years (Fisher, 2005; Kong, 2005). According to Norris (1985), critical thinking is not an educational choice but all students should be taught to think critically.

The first aim in this paper is to generate an operational description of critical thinking, based on an analysis of the literature. The second aim is to develop a test of critical thinking (for 13-15 year old learners) and gain evidence of its validity.

The History of Critical Thinking

Critical thinking is not a new phenomenon (Facione, 2009). Paul (1990) considers that the roots of critical thinking can be traced back 2500 years to Socrates, who revealed through questioning that most individuals could offer no rational justification for their strongly-held beliefs. However, John Dewey is often considered to be the originator of the modern-day tradition of critical thinking (Ennis, 1993; Fisher, 2005).

A key landmark came in 1962 with the article by Ennis entitled, '*A Concept of Critical Thinking*' (Ennis, 1962; Kong, 2005). Rather than focussing on the process of critical thinking, this concentrated on the quality of its products. Ennis redefined his original concept in the late 1980s, and included within it a process of critical thinking directed towards making decisions as to beliefs or actions (Ennis, 1989; Norris and Ennis, 1989).

The multiplicity of definitions for critical thinking can be attributed to the multiplicity of specialities among scholars. Logicians define critical thinking as arriving at results from premises; biologists define it as the attempts made