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The role of Visuospatial Working Memory in Chemistry Learning Assessed in a Sample of Italian Undergraduate Students

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Abstract

Chemistry learning and understanding depends on the ability to think circularly at three levels: the macroscopic, the sub-microscopic, and the symbolic level. This ability is mostly given for granted in higher education, although many students struggle in representing the sub-microscopic level, which is outside their range of experience. In addition, handling these three levels at a time may easily overload the Working Memory (WM), thus hindering meaningful learning. It has been demonstrated that success in chemistry learning correlates with good visuospatial abilities as well as with WM capacity. Nevertheless, the knowledge about specific cognitive processes involved in chemistry learning is still limited, especially concerning undergraduates. The present work contributes to this goal by investigating the differential involvement of verbal and visuospatial WM components in chemistry learning. We evaluated a sample of 315 undergraduates with a chemistry task (CT), and a subset ($N=81$) with three different cognitive tasks (the Listening Span Test, the Imaginative Puzzle, and the Cattell's Fluid Intelligence Test), aimed at assessing the verbal WM, the visuospatial WM and the estimated IQ, respectively. We sought correlations between WM components and chemistry performance: our results highlight a positive correlation between accuracy in performing the chemistry task and performance in the visuospatial WM task. Supplemental analysis compared the role of WM components in relation to the types of chemistry task questions (textual or visual). Our results showed that good visuospatial WM performance promoted the accuracy of students' performance when they were asked to manipulate both textual and visual information; this advantage was enhanced when visual information was involved.

Keywords visuospatial WM · chemistry learning · undergraduates students · chemical education

Introduction

The act of learning, according to the cognitivist approach, requires the constant effort to integrate new information with previous knowledge, stored in the long-term memory (LTM). New information is handled by the Working Memory (WM), that works synergistically with LTM, drawing from the latter previous knowledge and integrating them together, in order to meaning making (Reid, 2021). WM has been defined as a limited-capacity system that allows the

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retention and manipulation of verbal and visuospatial information (Baddeley, 2000; Hitch et al., 2025). Other theoretical frameworks, such as the Dual Coding Theory (Paivio, 2014; Paivio & Clarck, 2006) and Mayer's Multimedia Learning Theory (2005), posit that verbal and nonverbal (images) information is processed by humans throughout two subsystems that are separated, but interconnected. In order to understand how this integration is possible, the theoretical framework of the WM model (Baddeley, 2000; Baddeley & Hitch, 1974; Hitch et al., 2025) looks suitable. In fact, according to this model, WM consists of two domain-specific components: the phonological loop (involved in processing verbal information) and the visuospatial sketchpad (involved in processing visual and spatial information). They are linked through the episodic buffer (that integrates verbal and nonverbal information and helps merging new information with that stored in the LTM). All these components are coordinated by the central executive, a limited-capacity attentional control system, which mediates the flow of information (Baddeley, 2000; Baddeley & Hitch, 1974; Hitch et al., 2025). Once new information is processed and successively stored in the LTM, the WM is then cleared for the next bunch of information (Reid, 2021, pp. 34–37). According to Reid (2021, p.31), this process implies that "*What we already understand allows us to make sense of what is new*, *the working memory being central in gaining understanding*".

Within this picture, chemistry meaningful learning implies additional complexity, related to the very nature of the chemistry discipline: in fact, understanding chemistry needs the flexibility and the ability to connect three different levels of reality: the macroscopic, the sub-microscopic and the symbolic one (Chittleborough, 2014; Johnstone, 1982, 1991, 2000). The first one includes all chemical phenomena perceptible by the senses of learners (Reid, 2014, 2021), i.e. what can be seen, touched and smelt (Taber, 2013). The sub-microscopic level refers to the interpretation of macroscopic phenomena in terms of interaction between microscopic particles (electrons, atoms, molecules, ions, etc…), hence it implies modeling activities. The symbolic level is the representational one: it includes chemical symbols, formulae, chemical/mathematical equations, graphs, reaction mechanisms, etc., and it refers to either the macro or the sub-micro-levels (Johnstone, 2000; Taber, 2013). The ability to connect and move through these three levels is crucial to chemical reasoning and lays behind students' troubles in understanding chemistry (Johnstone, 1991). This multilevel thought is especially necessary to undergraduate students, that approach chemistry at a higher conceptual level as compared to school students. Unfortunately, it places a heavy strain on WM, whose capacity risks to be overwhelmed (Johnstone, 2000; Reid, 2021; Taber, 2013). Therefore, students who succeed are typically those who implement strategies that decrease the risk of WM overload, such as 'chunking the information' (i.e. the ability to group small individual pieces of information together, to create a meaningful whole or identify patterns); or those with a field-independent cognitive style (i.e. the ability to 'select message from the noise', see Al-Naeme, 1988; Christou, 2001; Danili, 2001; Hindal et al., 2009).

Several studies that investigate the cognitive processes engaged in science learning are available in the literature (e.g., Berkowitz, 2018; Bull et al., 1999; Bull & Scerif, 2001; Flowers et al., 2013; Gathercole et al., 2004; Giofrè et al., 2018; Hinze et al., 2013; Jarvis & Gathercole, 2003; Kyttälä et al., 2003; Kyttälä & Lehto, 2008; Latzman et al., 2010; St Clair-Thompson & Gathercole, 2006). However, their number drops significantly when considering those focused on chemistry learning (e.g., Chandran et al., 1987; Hindal et al., 2009; Hindal et al., 2013; Kiernan et al., 2021; Reid, 2021, chapt. 2 and ref. therein; Rhodes et al., 2016; Stamovlasis & Papageorgiou, 2012; Taber, 2013; Taber & García-Franco, 2010; Talanquer, 2022; Zhang et al., 2021) and - even more - when taking into account those involving undergraduate students (e.g., Pribyl & Bodner, 1987; Sorby et al., 2020; Stieff et al., 2012).

It has been shown that chemistry understanding relies on domain-specific[1] cognitive processes (e.g., vocabulary, computing ability, a wealth of theoretical knowledge, etc…) as well as on domain-general[2] ones, including problem-solving, attention, inhibition, and working memory.

Due to the nature of WM and the role it plays in learning, WM capacity and efficiency are crucial in determining students' performance in chemistry learning: a low WM capacity could be a serious obstacle to succeeding in chemistry (Reid, 2014, 2021, chapt. 2 and ref. therein). This evidence is supported by several studies that relate chemistry performance and WM. For example, Rhodes et al. (2016) investigated this relationship among 7th -8th grade students, through a correlation and a linear regression analysis. They assessed both factual and conceptual knowledge of some chemical issues through a brief test. The authors refer to "factual knowledge" as a kind of knowledge based on the retrieval of information from long-term memory. Conversely, "conceptual knowledge" implies individual elaboration of the information: in other words, students are asked to reason further, in order to fully understand a specific topic. Authors' results pointed out that students'

[1] Domain-specific: cognitive processes assigned in processing information within a particular content area or type of knowledge.

[2] Domain-general: cognitive processes that are not related to a specific subject area but are involved in a wide range of cognitive tasks and in different learning contexts.

achievements correlated with WM performance, and - more specifically - conceptual learning was related to visuospatial WM component. Hindal et al. (2009) showed that WM capacity correlates positively and significantly with the outcomes of an ad hoc test measuring visuospatial abilities. Silverman (2002) found that many highly gifted visuospatial learners were successful at many tasks given in many ways. Reid (2021, p.32) reports that the efficiency of visuospatial WM component relates to chunking abilities.

Another aspect of the relationship between WM and chemistry learning deals with students' motivation: Jung and Reid (2009) showed that highly motivated chemistry teen-age students are generally characterised by high WM capacity. In fact, students with low WM capacity rely on memorisation to cope with exams; consequently, their interest for the subject drops.

Evidence discussed so far referred to school students. Few other studies showed that the variability of chemistry performance is also related to visuospatial ability: in particular, students with higher scores in a mental rotation task were better chemistry performers (Carter et al., 1987; Pribyl & Bodner, 1987; Sorby et al., 2020; Stieff et al., 2012). In fact, chemical classes implemented in high-level education (e.g., high school or university) address complex explanations asking students to deal with abstract concepts: students need to recall theoretical knowledge stored in long-term memory, and to integrate it with newly acquired information. WM supervises the processing, the maintenance, and the manipulation of all these aspects. Additionally, even though these students are asked to deal with abstract ideas, their ability to integrate the three levels of representation of chemical phenomena is often taken for granted and the related overload of WM is often overlooked (Johnstone, 2000; Reid, 2021). Unfortunately, none of the previous-cited studies explores the different contribution of verbal and visuospatial WM components in performing specific chemical tasks.

In summary, the involvement of WM in chemistry learning among teen-age students is clear (e.g., Danili & Reid, 2004; Hindal et al., 2009, 2013; Rhodes et al., 2016); nevertheless, investigations on university students, that are faced to highly demanding tasks at the cognitive level, are still limited. As these tasks require the activation of WM, our working hypothesis – based on the available literature - is that chemistry learning at university grade loads significantly on WM capacity and efficiency.

Our research question is the following: do verbal and visuospatial WM components play a different role in determining students' performance in a chemistry task?

In order to answer this question, we designed an ad hoc chemistry learning task, that was administered to a large student population. A subset was further assessed with three cognitive tasks aimed at evaluating the verbal WM, the visuospatial WM and the estimated IQ, respectively. We expected the visuospatial WM component to be more related to chemistry learning than the verbal WM component. Additionally, we expected students with high visuospatial WM ability to perform better in a chemistry task focused on molecular structures. A further value of this investigation comes from the fact that this assessment was carried out on a sample of Italian undergraduates. The sample nationality is relevant due to the total lack of this kind of investigations on the Italian population of undergraduate students.

Methods

Participants

This study involved 315 undergraduates' Italian students (M_{age} = 20.2 years, SD=5.32) with typical developing, attending the first semester of the academic year at the University of Turin (N=140), the Polytechnic University of Turin (N=17) and the University of Palermo (N=158). The sample included 167 females (53.4%), 136 males (43.2%), 5 non-binary (1.6%), and 7 individuals who choose the option "I'd rather not answer this question" (2.2%). The students were enrolled in different degree courses: Biotechnology (N=63, 20.0%); Chemistry (N=68, 21.6%); Natural sciences (N=81, 25.7%); Biology (N=64, 20.3%); Engineering (N=17, 5.4%); Agricultural sciences (N=9, 2.9%); Gastronomical sciences (N=13; 4.1%). All students involved in this study had, at least, one general chemistry class in their academic curricula, but most of them were not enrolled in chemistry degree courses. All these students underwent the assessment of chemistry learning abilities.

In-depth analysis on the relationship between chemistry performance and WM ability was computed on a self-selected sub-set (81 students), made by those students who agreed in undergoing further assessment (a verbal and a visuospatial WM task). This sub-set was composed as follows: Biotechnology (N=4, 4.9%); Chemistry (N=12, 14.8%); Natural science (N=28, 34.6%); Biology (N=20, 24.7%); Engineering (N=17, 21.0%); additional information is reported in Table 1.

Instruments

Chemistry task (CT)

The chemistry task was implemented for the assessment of chemistry learning abilities and was realized in accordance with the learning task included into the Italian battery for the assessment of study ability among undergraduates (De

Table 1 Demographic features of students' sub-sample ($N = 81$): number (N) and percentage (%) of gender distribution, mean (M) and standard deviation (SD) of the estimated Intelligence Quotient (IQ), and of the age

	Gender				Estimated IQ		Age	
	Female	Male	Non-binary	NA	M	SD	M	SD
N	36	41	1	3	103.9	13.44	19.6	1.85
(%)	(45.0%)	(51.2%)	(1.3%)	(3.7%)				

Note. *NA* "I'd rather not answer this question"

Beni et al., 2014). In fact, the chemistry was structured likewise the standardized study task, with a slight change: students were asked to listen to a 20-min video-class (instead of studying a written text) and, after a 10-minute break, they performed a final test. The decision to rely on a video-lecture was dictated by the need to replicate an ecological learning situation (close to what students experience in their daily academic life) and to design a replicable assessment tool. Finally, we opted for a peculiar topic (liquid crystals) that is not addressed by general chemistry classes. This choice was due to three main reasons: (i) the need to exclude a previous-exposure effect; (ii) the fact that this topic is easily explainable and does not require prior peculiar conceptual knowledge in chemistry; (iii) the relationship between this topic and everyday life.

Therefore, students attended a 20 min-video-class during which a chemistry professor (X.X.) illustrates liquid crystals and provides some pieces of information about their history, their structural arrangement and their technological applications (e.g. liquid crystal displays). During this step, students were allowed to take notes. Later, they were given 10 min for reviewing autonomously. After a 10-minutes break, they were finally asked to perform a multiple-choice test (four alternatives each) designed to assess their chemistry knowledge acquisitions. This test included 10 questions (see Table 2): five of them were textual (questions and alternatives answers are expressed as words), five were visual (questions are in words and the possible answers are pictures). Questions were developed by a multidisciplinary team of experts in chemistry and psychology: they were selected from an original pool of 15, based on the type of knowledge (factual or conceptual) and the cognitive processes involved (e.g. decoding, recall of lecture information, inhibition, inference). We define factual question as those in which the propter answer mainly relies on the recall of information; whereas, conceptual questions are those that require the student to carry out further reasoning in order to reach a deep-level understanding. A classification of the 10 selected questions, based on the type of knowledge and cognitive processes involved, is reported in Table 2.

The final score was calculated as the sum of correct answers (maximum score = 10). The number of correct textual and visual responses was also determined separately (maximum score = 5 for both cases).

Verbal WM Component

The verbal WM component was assessed with an Italian version of the Listening Span Task (LST) (De Beni et al., 2008). Students were asked to listen to five sets of sentences (the number of sentences increased gradually from two to six). After each statement, they had 2 s for judging its truthfulness. At the end of each set, they had to recall the last word of each sentence in the correct order. For example, students listen to the following statements: "Human beings could survive even without *oxygen*" (False), "Soccer is a sport that is played exclusively in the high *mountain*" (False), and "It is possible to die if you are bitten by a *viper*" (True). Afterwards, they should recall the terms "oxygen", "mountain", and "viper" (an excerpt of this task is reported in Supplementary Material Table S1). The task assessment was adapted for collective administration. Then, students were asked to write down their answers. The final score corresponds to the number of words reported correctly. All the misspelled words written in the right order were counted as valid. According to the manual (De Beni et al., 2008) the split-half correlation is $r = .87$.

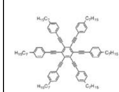
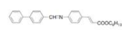
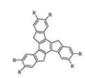
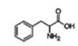
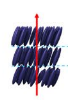
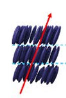
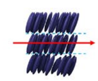
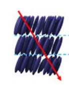
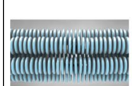
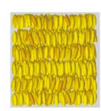
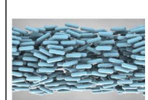
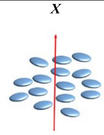
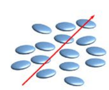
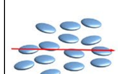
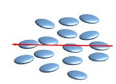
Visuospatial WM Component

The visuospatial WM component was assessed with the Imaginative Puzzle (IP) task included in the Italian battery for the assessment of cognitive abilities in adulthood (De Beni et al., 2008). It consists of 27 items organized in nine levels (from level 2 to level 10, with three tasks per level) with increasing difficulty. In each task, students were asked to look at a picture of a usual object (e.g., some luggage, a telephone, a baby carriage, etc…) for 2 s. Then, the same item was presented shattered into multiple enumerate pieces, with the number of fragments corresponding to the level of difficulty (e.g., level 2 = two pieces, level 3 = three pieces, etc…). Then, students were asked to mentally reassemble the fragments in the right position, and to write them down in a given matrix (an excerpt of this task is reported in Supplementary Material Table S1). According to the manual (De Beni et al., 2008), each level was passed by performing at least 2 fully correct tasks per level. The final score is obtained by

Table 2 Percentage of students' accuracy in each chemistry question, categorized by type of knowledge (factual or conceptual) and cognitive process involved (decoding, recall of lecture information, or inference)

Question's number	Percentage of accuracy (N= 315)	Question	Alternatives	Cognitive processes involved
Q1 (Factual)	74.9%	Quando è stato coniato il temine cristallo liquido? [When was the term 'liquid crystal' first used?]	• Fine '700 [At the end of 18th century] • Anni 50 del '900 [1950s] • ***Fine '800 [At the end of 19th century]*** • Anni 90 del '900 [1990s]	Decoding Recall
Q2 (Conceptual)	76.8%	La formazione di un cristallo liquido può essere determinata da: [The formation of liquid crystals can be determined by:]	• Una variazione di densità [A density change] • ***Una variazione di temperatura [A temperature change]*** • Una interazione con la luce [An interaction with light] • Tutte le precedenti [All the above-mentioned alternatives]	Decoding Recall
Q3 (Conceptual)	72.1%	Nella fase nematica i mesogeni [In the nematic phase, mesogens:]	• ***Sono disposti secondo una direzione preferenziale [Are placed according to a preferential direction]*** • Presentano un ordine posizionale [They show a positional order] • Si distribuiscono in piani sovrapposti [They are organised in overlapping layers] • Occupano posizioni fisse [They have fixed positions]	Decoding Recall
Q4 (Factual)	84.4%	Nella fase smettica C: [In smettic C phase:]	• Non esiste un direttore preferenziale [There is no preferential director] • Il direttore e la normale del piano coincidono [The director and the normal to the plane coincide] • Il direttore e la normale del piano hanno direzioni opposte [The director and the normal to the plane have opposite directions] • ***Il direttore forma un angolo con la normale del piano [The director forms an angle with the normal to the plane]***	Decoding Recall Inference
Q5 (Conceptual)	35.6%	Quando si accende il campo elettrico in un pixel di uno schermo LCD [When the electric field is switched on in a pixel of an LCD screen:]	• ***La fase chirale non è presente e il pixel risulta spento [The chiral phase is destroyed, and the pixel is switched off]*** • La fase chirale è presente e il pixel risulta acceso [The chiral phase is created, and the pixel is switched on] • La fase chirale è presente e il pixel risulta spento [The chiral phase is created, and the pixel is switched off] • La fase chirale non è presente e il pixel risulta acceso [The chiral phase is destroyed, and the pixel is switched on]	Decoding Recall

Table 2 (continued)

Q6 (Conceptual)	38.4%	Quale delle seguenti immagini non corrisponde ad un sistema chirale? [Which of the following picture does not correspond to a chiral system?]			*X* 		Decoding Recall
Q7 (Factual)	41.6%	Quale delle seguenti strutture molecolari ti sembra adatta a formare dei cristalli liquidi calamitici? [Which of the following molecular structures is suitable for giving rise to calamitic liquid crystals?]		*X* 			Decoding Recall
Q8 (Factual)	67.6%	Osserva le figure sottostanti, che si riferiscono ad una fase smettica. Quale di esse individua correttamente il direttore? [Look the following pictures, which refer to a smectic phase. Which of them identifies the director properly?]		*X* 			Decoding Recall Inference
Q9 (Conceptual)	35.6%	Quale delle figure sottostanti corrisponde ad una fase nematica? [Which of the following pictures correspond to a nematic phase?]				*X* 	Decoding Recall
Q10 (Conceptual)	49.2%	Quale è il corretto direttore per una fase nematica discotica? [Which picture properly identifies the director in the discotic nematic phase?]	*X* 				Decoding Recall

summing up the number of the three most difficult tasks completed successfully by the student. For example, if a student reaches level 10 with all three fully correct tasks, the final score is 30 (10 + 10+10); if they reach level 10 and failed one task out of three, the total score is 29 (10 + 10+9); if they reach level 8 with all fully complete tasks, but they subsequently fail two tasks out of three in level 9, the total score will be 25 (8 + 8+9). According to the manual (De Beni et al., 2008) the Cronbach alfa is α = 0.83.

Estimated Intelligence Quotient (Estimated IQ)

The estimated IQ was measured using the Cattell's Fluid Intelligence Scale (Weiß, 2006). The manual includes two different scales (part 1 and part 2) and provides a measure of the IQ for each single scale or their combined administration (part 1 + part 2). For the present study, we choose to use only part 2, because it allows administration in shorter time, due to the reduced number of items. This scale includes four different types of problems, and each set is time limited. The first type is called *Series* (12 items, 3 min.): students look at a sequence of three items; then, they are asked to find the missing item (fit to complete the series) among five alternatives. The second type is called *Classification* (12 items, 3 min.): students are asked to choose the item that conflicts with the others, among a set of five items. The third class of subtests is *Matrix* (12 items, 3 min.): students have to find the correct alternative (among five) that completes a matrix accurately. The last one is *Analogies* (9 items, 3 min.): students look at a target made up of geometrical figures and one/two black dot/dots placed at a specific position with respect to the figures. Afterwards, they are asked to choose, among five alternatives reporting only the geometrical shapes, the one where dots can be placed in an analogous position as in the target. An excerpt of this scale is presented in Supplementary Material Table S1. The final score is the sum of the number of right answers. It is converted into the estimated IQ score, according to the normative tables included in the manual. Overall, the internal consistency of the current sample was good ($\alpha = 0.78$).

Procedure

Students were assessed with a chemistry task and with additional cognitive tasks. The assessment took place in two steps:

- *Assessment of chemistry learning abilities*: carried out during a collective session (duration approx. 1 h) in which students were asked to perform a chemistry task (described below); few personal details (age, gender, and type of degree course) were also collected during this phase.
- *Assessment of WM abilities*: carried out during another collective session (duration approx. 1 h) during which students were asked to perform a verbal and a visuospatial WM task. An estimated IQ (Intelligence Quotient) score was also measured through the Cattell's Fluid Intelligence Test, Scale 2 (Weiß, 2006).

Both the procedure and the methodology had been previously refined, through a preparatory investigation (De Vita et al., 2024). This exploratory study involved a small sample of Italian undergraduates' students ($N = 39$), who were assessed with similar tasks as the ones described in the present study. The results collected from the preparatory study proved the adequacy of our methodological approach. In addition, it allowed narrowing down the number of WM tasks proposed to students from four to two (i.e. those who turned out to correlate more significantly with the chemistry performance). Finally, this preparatory investigation showed that students who define themselves as primarily skilled in textual information processing perform better in textual questions than in visual questions; whereas those who define themselves as primarily skilled in image-related information processing perform the reverse (better in visual questions than in textual questions).

Data Analysis

Data analysis was computed with the Jamovi Project Version 2.3 (2022). A quantitative analysis of chemistry task (CT) features was implemented on the whole students' sample. Then, the relationship between chemistry task performance and cognitive abilities (verbal WM, visuospatial WM and estimated IQ) was determined through a correlation analysis and a linear regression analysis. Finally, we sought evidence of the differential involvement of visuospatial WM in promoting students' accuracy in textual and visual chemistry task questions. Consequently, we divided the sample in three groups, based on their performance in the Imaginative Puzzle task – IP (low: $IP \leq 21$; medium: $22 \geq IP \geq 27$; high: $IP \geq 28$) and we computed two separate one-way ANCOVAs, one for the textual and one for the visual questions, for comparing the differences in students' performance. The estimated IQ score was included as covariate.

Results

Chemistry task Quantitative Analysis

Students' accuracy for each question is reported in Table 2, and it was calculated as the ratio between the number of correct answers and 315. The results show that neither floor nor ceiling effects are present, since no question achieved 100% correct or incorrect answers. The degree of difficulty proved balanced: in fact, at least 50% of the sample answered 5 questions correctly (Q1, Q2, Q3, Q4, and Q8) and less than 50% of the sample found the right alternative in the other 5 questions (Q5, Q6, Q7, Q9, and Q10).

In addition, we calculated the score resulting from the number of right answers to these 10 questions either as a whole (max score = 10) and distinguishing between textual and visual questions (max score = 5 each). Mean and standard deviation of the total score were $M = 5.75$ ($SD = 1.83$). The same parameters for the textual and visual queries were $M = 3.44$ ($SD = 1.15$) and $M = 2.31$ ($SD = 1.18$), respectively. Overall, these data highlight distinct trends in the textual vs. visual results, as students achieve higher scores in the textual group of questions as compared to the visual group. The results of a paired t test prove that such difference is meaningful, $t(314) = 13.9$, $p < .001$, *Cohen's* $d = 0.78$.

Nevertheless, it's worth underlining that some questions do not fit this pattern, as Q5 reaches a much lower score than the other textual questions, just as Q8 reaches a higher score as compared to questions of the same visual group. A similar trend was found in the preparatory study (De Vita et al., 2024).

Results of the Cognitive Ability Assessment and Relationship Between Chemistry task (CT) Performance and Cognitive Tasks

The present study aims at shedding light on the cognitive processes that are specifically involved in chemistry learning and understanding. Consequently, the chemistry task assessment was followed by an assessment of cognitive abilities. Since participation in the study was voluntary, only part of the sample (N=81) adhered also to the second step. Students' performance on this self-selected sample was analysed in order to find correlations, if any, between students' achievements in the CT and their WM and cognitive abilities (estimated Intelligent Quotient). Table 3 reports: (i) the results of students' performance in CT calculated over the student sub-set; (ii) the descriptive of the outcomes of the cognitive tasks assessment; (iii) the results of the correlation analysis.

Data show very strong positive correlation between chemistry task Total and chemistry task Textual scores, and between chemistry task Total and chemistry task Visual scores. Interestingly, a weak positive correlation between visual and textual questions has been detected. In addition, a moderate positive correlation between Imaginative Puzzle task score and chemistry task performance (both the total and the textual score) is evident. Finally, a moderate positive correlation between Imaginative Puzzle task score and the estimated Intelligent Quotient has been found, as well.

Hence, we decided to compute a linear regression analysis in order to investigate if the cognitive tasks' performance and chemistry task performance are related. Therefore, chemistry task Total score was considered as the dependent variable and the cognitive tasks (Estimated Intelligent Quotient - IQ, Imaginative Puzzle task -IP, and Listening Span Task -LST) as predictors. The results pointed out that the Imaginative Puzzle task performance (assessing visuospatial WM component) is the only one that relates significantly to the chemistry task Total score. More precisely, our findings show that subjects with high Imaginative Puzzle task score achieved high scores in chemistry task, too. The results of the linear regression analysis are reported in Table 4.

The results of the linear regression analysis corroborate those of the correlation analysis: they point out that the total score in the chemistry task is significantly related to the performance in the Imaginative Puzzle task. Conversely, the other predictors (Listening Span Task that assesses verbal WM component, and the estimated IQ) do not significantly affect chemistry learning performance in this task.

Finally, we divided the sample in three groups, based on their performance in the Imaginative Puzzle task (low: IP≤21; medium: 22≥IP≥27; high: IP≥28) and we computed two separate one-way ANCOVAs in order to find possible differences between the IP groups and students' performance in the textual and visual questions of the chemistry task (see Figs. 1 and 2, respectively). The estimated IQ score was included in both analysis as a covariate variable.

The one-way ANCOVA on textual questions pointed out a meaningful effect of the Imaginative Puzzle group $F(2,77)=5.11$, p = .008, η^2_p = .117; while the covariate,

Table 3 Mean (M), standard deviation (SD), and correlation analysis between all the variables

Task				Spearman's Rho					
	N	M	SD	1	2	3	4	5	6
1. Chemistry Task Total	81	6.16	1.76	1					
2. Chemistry Task Textual	81	3.48	1.23	0.80**	1				
3. Chemistry Task Visual	81	2.68	1.07	0.73**	0.17	1			
4. Estimated IQ	81	103.09	13.44	−0.04	−0.03	0.03	1		
5. IP (visuo-spatial WM)	81	24.7	4.25	0.29**	0.24*	0.21	0.34*	1	
6. LST (verbal WM)	81	17.1	2.79	0.07	0.11	−0.01	0.25*	0.08	1

Note. * p < .05; ** < 0.001. *IQ* Intelligence Quotient, *IP* Imaginative Puzzle, *LST* Listening Span Task

Table 4 Linear regression analyses predicting chemistry task total score

Intercept	B	SE	t	p	β	95% IC	
	4.44	1.77	2.51	0.014			
IP	0.14	0.05	2.98	0.004	0.34	0.11	0.57
LST	0.03	0.07	0.45	0.655	0.05	−0.17	0.27
Estimated IQ	-0.02	0.02	-1.46	0.149	−0.17	−0.40	0.06
	F (3,77)=3.20, p = .028, R^2*adjusted = 0.076*						

Note. Predictors were performance in the Imaginative Puzzle (*IP*) task, Listening Span Test (*LST*), and estimated Intelligence Quotient (*IQ*)

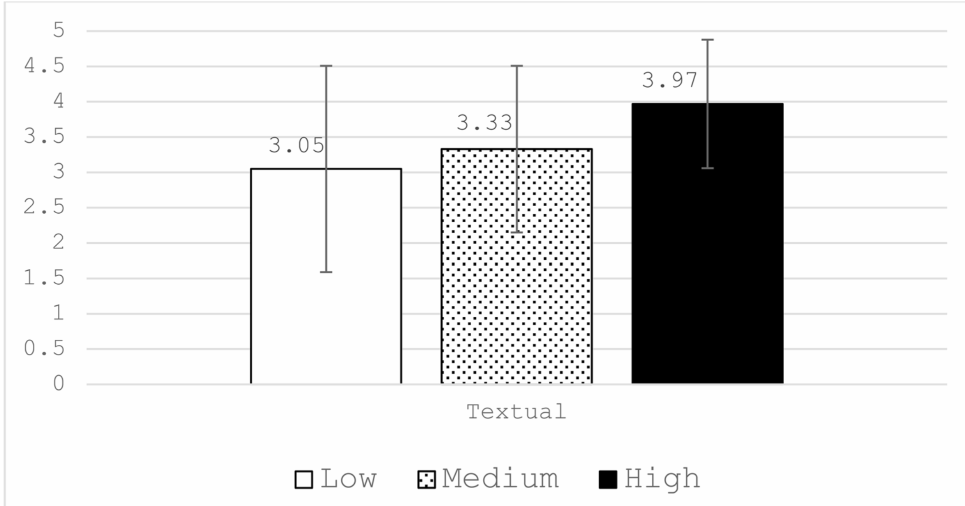


Fig. 1 Mean of CT Textual scores in the three groups (low, medium and high IP score)

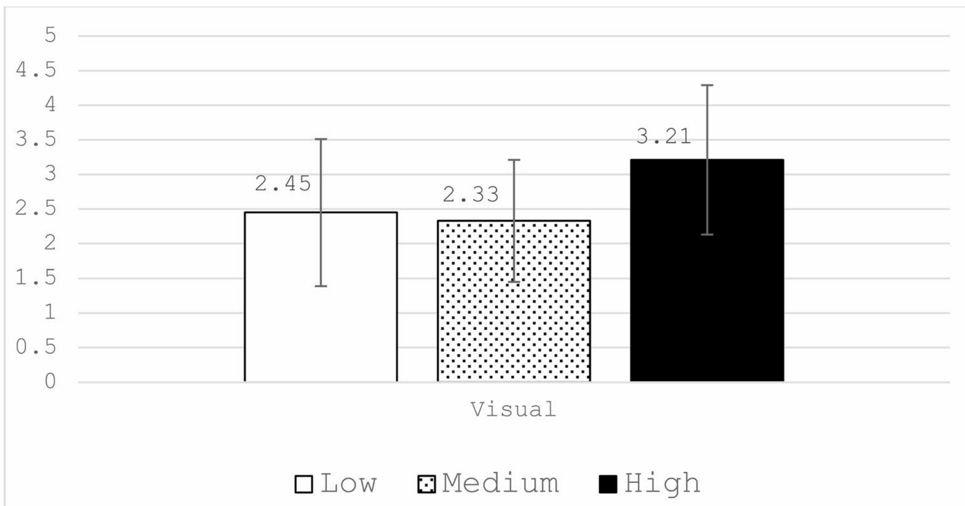


Fig. 2 Mean of CT Visual scores in the three groups (low, medium and high IP score)

estimated IQ, was found not significantly related to the accuracy in textual questions $F(1,77)=1.86$, p = .177, η^2_p = .024. The descriptive statistics are reported in the Supplementary Material (Table S2). In particular, the results of the *post-hoc* tests, adjusted according to Bonferroni, showed that students with low Imaginative Puzzle performed worse as compared to those with high Imaginative Puzzle score, $t(77)=3.06$, p_{adj} < 0.01, *Cohen's d* = 0.91. On the other hand, no differences were found between students with low vs. medium Imaginative Puzzle score, $t(77)=0.97$, p_{adj}> 0.05, *Cohen's d* = 0.27, nor between students with medium vs. high Imaginative Puzzle score, $t(77)=2.36$, p_{adj}> 0.05, *Cohen's d* = 0.64.

The one-way ANCOVA on visual questions led to similar results, as we found a significant effect of the Imaginative Puzzle group $F(2,77)=7.57$, p< .001, η^2_p = .164, and no meaningful effect of the covariate, estimated IQ score $F(1,77)=2.36$, p= .128, η^2_p = .030. Descriptive statistics are reported in Supplementary Material (Table S2). The results of the *post-hoc* tests, adjusted according to Bonferroni, shows that the group with high Imaginative Puzzle score performed significantly better as compared to the low Imaginative Puzzle group, $t(77)=3.02$, p_{adj} = 0.01, *Cohen's d* = 0.90, and the medium Imaginative Puzzle groups, $t(77)=3.65$, p_{adj}= 0.001, *Cohen's d* = 0.99, whereas no differences were found between low and medium Imaginative Puzzle score groups, $t(77)=0.33$, p_{adj}> 0.05, *Cohen's d* = 0.09.

Discussion

The present study investigates the differential involvement of verbal and visuospatial WM components in explaining undergraduate students' performance in a chemistry learning task. Our final aim was to establish whether verbal and visuospatial WM components play distinct roles in determining students' performance in a specific chemistry task. The chemistry task was designed by a multidisciplinary pool of chemistry and psychology experts; it aims at tackling some abilities that are especially prompted in chemistry students when they deal with basic chemical issues that are crucial for a comprehensive understanding of chemistry (e.g. chirality, molecular and supramolecular structures, isomery, molecular geometry, molecular dynamics, etc.). Nevertheless, we choose a chemical topic (liquid crystals) that is not included in general chemistry classes. The advantages of this choice are multifarious: (i) it avoids previous-exposure effect; (ii) it is accessible to students with minimal chemistry background; (iii) it has a motivational strength, as it is strictly related with learners' experiential world, due to its involvement in many technological devices of daily use (cell phones screens, etc.). Point ii) is especially relevant as we choose to assess students not necessarily enrolled in chemistry degree courses. This choice is justified in the context of scientific studies, where chemistry is part of the basic curriculum of several disciplines (e.g. biology, earth science, natural sciences, biotechnology, engineering, agricultural science). The chemistry content of these non-chemistry curricula is limited, but essential for understanding these other disciplines. These students are generally little motivated towards chemistry; nevertheless, they have to cope with numerous challenges associated with chemistry learning (e.g. the difficulties of chemical multilevel thought, the difficulty to imagine a microscopic realm that is not accessible to senses and requires marked abstraction abilities, etc.). Therefore, we choose a topic that could motivate them.

In order to achieve the aim of assessing whether verbal and visuospatial WM components are differently involved in students' chemistry performance, this investigation focused on both disciplinary knowledge and cognitive processes; hence, the dual design of the students' assessment, with a chemistry task and cognitive tasks. The adequacy of this protocol was tested with a preparatory investigation (see De Vita et al., 2024).

The present outcomes of the chemistry task reveal that there are different trends in the students' performance with regard to textual and visual, as the latter result in lower average scores. This difference is not imputable to a greater difficulty of visual questions: in fact, both textual and visual questions were balanced in terms of type of knowledge (factual or conceptual[3]) and type of cognitive processes (decoding, recalling, inhibition and inference) involved (see Table 2).

[3] For the definition of factual and conceptual knowledge, see the 'Instruments' section.

One might wonder if the lower performance in visual questions is due to a lack of familiarity of Italian students with this kind of formulation. Nevertheless, the misaligned scores of textual Q5 (most students answer incorrectly) and visual Q8 (most students answer correctly) do not support this interpretation. In fact, Q5 insists on conceptual chemical aspects that require deep-level comprehension of chemical issues. So, despite its belonging to the textual group of questions (that achieved higher scores, overall), this specific result is imputable to both conceptual difficulties and cognitive aspects (i.e. weaker WM resources, and a field-dependent cognitive style). On the contrary, Q8 involves visuospatial WM, but does imply neither the active manipulation of visual information nor complex conceptual issues (surface comprehension level). The opposite occurs in visual Q9 and Q10, which, in fact, attain much lower scores. Specularly, the high score of textual Q4 is justified by the fact that it does not require deep-level comprehension. Therefore, we conclude that the distinct trends of students' performance in textual vs. visual questions are not dependent on how these questions are formulated, but truly reflect a different mobilisation of cognitive abilities. The overall outcomes of the chemistry task are also coherent with the evidence that cognitive tasks implying the recall, integration and manipulation of information are more demanding than those just involving maintenance, due to the enhanced involvement of WM (Crone et al., 2006; Johnstone, 2000; Reid, 2014).

The outcomes of the correlation analysis show that the scores of textual and visual questions are not mutually correlated, but each one correlates positively with the total chemistry task score. This result corroborates a previous explorative study (De Vita et al., 2024) which demonstrated that textual and visual questions were not significantly correlated; instead, these scores were related to students' cognitive styles (verbal vs. visual). Students with main verbal cognitive style reached higher scores in the textual questions, and vice-versa. The correlational output found in the present study, in line with these previous results (De Vita et al., 2024), entails deep implications for chemical education: in fact, some chemical topics (e.g. stoichiometry, concentration calculations, applications of mathematical laws to the chemical realm, etc.) are more related to verbal, mathematical and problem-solving abilities, whereas others (chirality, molecular and supramolecular structures, molecular dynamics, etc.) require strong visuospatial abilities, as students need to develop mental representations of a level of reality inaccessible to senses.

Based on our research question, we sought correlation between the results of the chemistry task and the outcomes of the cognitive tasks. We found a significant positive correlation between the Imaginative Puzzle task score (assessing visuospatial WM component) and the chemistry task scores (total, textual and visual), whereas no significant correlation between Estimated IQ and chemistry task scores was highlighted. This is in line with our working hypothesis, as it shows that only the visuospatial component correlates significantly with the chemistry task. Interestingly, we also found significant correlation between the Imaginative Puzzle task score and textual questions. This suggests that even this type of questions relies inherently on visuospatial WM abilities, due to the nature of the chosen topic (liquid crystals). This evidence is also coherent with other theoretical frameworks, such as Dual Coding Theory (Paivio, 2014; Paivio & Clarck, 2006) and Mayer's Multimedia Learning Theory (2005). In fact, during the video-class, students were exposed simultaneously to verbal (speech) and nonverbal (images) information. According to these theories, these two types of information are processed by two separated subsystems. Since the deep-level understanding of the video-class relied mainly on nonverbal information, this is consistent with the significant correlation found between chemistry task performance (total, verbal and visual scores) and visuospatial WM component.

The lack of significant correlation between chemistry task and Estimated IQ suggest that students' performance cannot be explained by their general cognitive ability. These results have been further upheld by the outcomes of linear regression analysis that shows that students' performance in the chemistry task (total score) is significantly related only to the visuospatial WM component. The other predictors (Estimated IQ and verbal WM component) turn out to be not significant. These findings are consistent with previous work on the crucial role played by visuospatial abilities in predicting chemistry learning performance (e.g. Carter et al., 1987; Hindal et al., 2009, 2013; Johnstone, 2000; Pribyl & Bodner, 1987; Reid, 2014; Sorby et al., 2020). Within this frame, our study provides further insight on the different role played by verbal and visuospatial WM in chemistry learning. Our findings corroborate those by Rhodes et al. (2016) who report the different engagement of the two domain-specific WM systems in predicting chemistry performance among adolescents, and extend them to undergraduates' population.

In the light of the findings discussed so far, a further question arises: can the performance in textual vs. visual questions benefit differentially from visuospatial WM abilities?

The ANCOVAs helped answering this question as students with high visuospatial WM ability answered more accurately in both textual and visual questions as compared to the group with low and medium visuospatial WM ability. Moreover, this advantage is greater when students need to recall and manipulate visual material. This suggests that students who are more acquainted with creating mental representations of abstract concepts (such as the visualisation of molecular structures, molecular interactions, chiral centres, molecular symmetry, etc…) achieve understanding of these concepts more easily than students that are not endowed with good visuospatial WM ability. This may also be related to the fact that the visuospatial WM component may act as a chunking device (Reid, 2021), and students with high visuospatial WM are more efficient and less cognitively overloaded during the learning process.

As the last point, we would like to mention some limits of the present study. First, we assessed verbal and visuospatial WM through a single task; however, previous investigation demonstrated that only these two WM tasks correlate significantly with the chemistry task performance. Second, it might be worth investigating the role of other cognitive processes involved in chemistry learning, such as attention, planning, problem-solving, further visuospatial abilities (implemented as the ability to mentally rotate and manipulate 3D elements). Third, we assessed IQ score with the Cattell's Fluid Intelligence Test (CFT) that provides a total IQ esteem. Besides, the CFT assesses intelligence through four different visual problems, only. It might be worth including more complete IQ assessment instruments (such as Wechsler scales) in further investigations. Fourth, the present study was conducted exclusively on Italian undergraduate students, which constrains the generalizability of the findings. Future research should extend this investigation to students from different countries and educational contexts, in order to assess whether the prominent role of visuospatial working memory in chemistry learning is consistent across diverse cultural and academic backgrounds.

Conclusions

This study project aimed at establishing the distinctive relationship between verbal and visuospatial WM components and undergraduate students' performance in a chemistry learning task designed *ad hoc.* Despite the availability of a number of investigations covering the role of cognitive processes in chemistry learning, very few data have been collected among undergraduates. Our study addresses this educational level; in addition, it was carried out on a population of Italian undergraduates, who suffer a total lack of investigations concerning the cognitive processes involved in chemistry learning.

Overall, the present study shows that:

- The research hypothesis concerning the differential role played by verbal and visuospatial WM components in chemistry learning is confirmed.

- Only visuospatial WM component positively correlates with students' performance in the chemistry task; in fact, our results show that good visuospatial WM performance promoted the accuracy of students' performance when they were asked to manipulate both textual and visual information; this advantage was enhanced when visual information was involved.
- As chemistry learning relies to a significant extent on the manipulation of spatial representations of the microscopic realm, it is precisely the visuospatial WM component that risks to be overloaded.

Consequently, the task of learning foundational chemistry concepts may benefit from the introduction of visualisation tools aimed to support students in building mental representations of the microscopic level. In fact, these may compensate weaknesses in visuospatial WM component and improve efficiency in exploiting this component as a chunking device (Reid, 2021).

The present investigation is an example of the benefits deriving from mutual cooperation between different areas of expertise (i.e. the psychological and the chemical areas of knowledge), which turns to be crucial for spotting out the cognitive abilities involved in learning specific chemistry contents. In perspective, these results may have relevant educational implications, as they could inform the implementation of didactic strategies helpful to students with low visuospatial WM abilities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10956-026-10336-2.

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Author Contribution Antonella Maggio, Renato Lombardo, Barbara Sini, Anna Maria Re, and Francesca De Vita conceptualised and designed the study and the methodology. Francesca De Vita, Antonella Maria Maggio, Renato Lombardo, and Elena Ghibaudi were responsible for the investigation, and the data collection. Francesca De Vita, and Anna Maria Re were responsible for the data curation, and the data analysis. Elena Ghibaudi, Francesca De Vita and Anna Maria Re wrote the first draft of the manuscript, and the subsequent revisions. All authors reviewed and approved the final manuscript.

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Data Availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics Approval The study received the approval of the Bioethical Board of the University of Turin (dossier number 0059554 dated 30/01/2023).

Competing Interests The authors report there are no competing interests to declare.

Informed Consent All the participants signed a written informed consent form before the experiment. Consistent with the approved protocol, they were informed that they had the right to withdraw from the experiment at any time.

Consent to Participate Informed consent was obtained from the participants in the study.

Consent to Publish Not applicable.

Statement Regarding Research Involving Human Participants and/or Animals All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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