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Investigating the differential effect of static pictures versus dynamic animations on students' performance in a chemistry learning task performed by Italian undergraduates

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Abstract: The ability to comprehend the sub-microscopic dynamics underlying macroscopic phenomena and to represent them through symbolic languages is often taken for granted in undergraduate students. Nevertheless, evidence shows that difficulties in connecting these three dimensions persist even at the university level. In recent years, several researchers have investigated whether visualization tools can help students overcome this challenge. However, the literature presents conflicting evidence, and a more comprehensive understanding could be achieved by incorporating information about students' cognitive profiles. The present study investigates the effectiveness of different representation modalities (static pictures vs. dynamic animations) in a lecture on liquid crystals, and their relationship with students' visuospatial and verbal working memory and fluid intelligence. We assessed 205 Italian students enrolled in scientific degree programs requiring at least one chemistry exam. Students watched a video-recorded lecture about liquid crystals and completed a multiple-choice test assessing their comprehension. In addition, students completed three standardized cognitive tasks measuring visuospatial and verbal working memory and fluid intelligence. Despite exhibiting lower cognitive abilities, students exposed to dynamic representations achieved equivalent results in the chemistry task. Furthermore, analyses demonstrated that dynamic animations benefit students with low visuospatial working memory capacity, levelling performance differences that emerged in the static condition.

Keywords: chemistry education; working memory; dynamic and static visualization; eurovariety 2025

1 Introduction

Chemistry is a complex discipline, that can be challenging for both students and educators, as it has been demonstrated by Johnstone.[1,2] In fact, mastering chemistry relies on the ability to navigate and interrelate three

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distinct levels of reality: macroscopic, sub-microscopic, and symbolic.[2–5] The macroscopic one encompasses all chemical processes that are detected through human senses; in other words, it refers to what can be visually observed, physically touched, or perceived through smell.[6–8] At the sub-microscopic level, people interpret the observable phenomena by examining the interactions among sub-microscopic entities such as atoms, molecules, ions, and electrons. Finally, the symbolic level encompasses the several representational tools such as chemical symbols, formulae, chemical/mathematical equations, graphs, and reaction mechanisms, which can refer to either the macroscopic or sub-microscopic levels.[5,8] Chemical thinking requires to integrate and shift through these three dimensions: this ability represents a primary source of difficulty for chemistry learners.[2] In fact, according to Johnstone,[1,2,4,9] most difficulties in chemistry learning derive from the combination between limited working memory resources and the practice of the multi-level thought described above: these two factors result in a significant cognitive demand.

In order to improve our understanding of the cognitive processes implied with chemistry learning, it is useful to integrate chemistry education with cognitive psychology issues. From the psychological viewpoint, understanding chemistry relies on domain-specific cognitive processes (such as vocabulary, computing ability, and a wealth of theoretical knowledge) as well as on domain-general ones, i.e. general mental abilities that are not tied to a specific discipline, but support learning and performance across different academic domains (according to cognitive psychology). The most studied domain-general cognitive processes related to chemistry education are executive functions, working memory, visuospatial ability, and fluid intelligence. Executive functions define goal-oriented cognitive processes that control and monitor human behaviour, thereby promoting the achievement of set goals.[10–12] Working memory, introduced by Baddeley,[13,14] is the mental workspace where information is dynamically handled, manipulated, and integrated with knowledge stored in long-term memory. It consists of two domain-specific components: the visuospatial sketchpad and the phonological loop are responsible for processing visuospatial and verbal information, respectively. They are connected via the episodic buffer, a limited-capacity system that temporarily stores and integrates information from multiple sources, linking new knowledge to long-term memory. All of these components are coordinated by the central executive, a limited-capacity attentional control system that mediates the flow of information.[13,15] Visuospatial ability refers to a set of mental processes that enable individuals to encode, store, process, and manipulate visual and spatial information, such as the mental rotation of objects and the identification of simple shapes within complex figures.[16,17] Finally, fluid intelligence can be described as the ability to intentionally recognize rules and patterns, enabling the resolution of novel tasks that cannot be solved through automatic procedures.[18,19]

Students' differences in learning/understanding chemistry topics are partially explained by domain-general cognitive processes.[20] However, the complexity of the subject and the wide range of topics and subfields covered by chemistry education make it more difficult to reach a definitive conclusion on the role of various cognitive processes in chemistry learning.

1.1 Cognitive processes and chemistry learning

A number of studies have attempted to measure the relationship between cognitive processes and chemistry learning/academic performance.[20–42] Alex Johnstone's seminal studies integrated chemistry education with the cognitive psychology perspective.[1,43,44] Johnstone argued that students' difficulties in chemistry stem largely from the cognitive effort required to shift between the three levels of reality (macroscopic, sub-microscopic, and symbolic), which places a heavy burden on domain-general cognitive resources.

With regard to visuospatial abilities, one of the main challenges stems from the effort required to form mental representations of the chemical concepts and models associated with the submicroscopic level of chemistry, that cannot be directly observed. For example, investigations on the relationship between mental rotation ability and visuospatial skills have highlighted a positive correlation with students' ability to identify 2D and 3D representations of chemical structures or with their accuracy in drawing these structures.[23,25,32,37] Interestingly, according to Stull et al.[37] this correlation was weaker when students were provided with a three-dimensional stick-and-ball models. Overall, several research findings highlight the central role of visuospatial ability in chemistry learning, particularly when students are required to deal with the sub-microscopic and symbolic levels of reality.

Turning to the role of working memory in chemistry learning, this has been studied primarily in relation to problem-solving activities.[27,36,38,39,45,46] Scholars such as Niaz[27] and Tsaparlis[38,39] rely on the concept of M-demand, defined as the number of cognitive resources a person must activate simultaneously to perform a specific task. In other words, it indicates the extent of working memory load during a specific task. In general, WM load has a greater impact in problem-solving activities that require students to process various pieces of information simultaneously, no matter which grade they belong to. Niaz[27] showed that students with high scores in the cognitive tasks (measuring visuospatial skills, working memory and reasoning skills) performed better in chemistry problems with high M-demand. Investigations performed by Tsaparlis and collegues[36,38,39,45,46] on various age groups, from 11th grade to college freshmen, shows that WM overload can be better understood by taking into account logical thinking and visuospatial skills: weaknesses in these cognitive processes can impair the overall efficiency of WM. Moreover, Tsaparlis[38] explored the relationship between students' performance during chemistry exams and the verbal and visuo-spatial components of WM (relying on the Backward Digit Span Task and the Figural Intersection Test, respectively). The impact of visuo-spatial components proved higher as compared to the verbal component. The pivotal role of visuospatial WM component in chemical problem-solving tasks was further confirmed by Upahi et al.[40]

Let's turn to the role of executive functions and fluid intelligence in chemistry learning. Li et al.[25] showed that students' cognitive flexibility,[1] measured with a visual switching task,[2] correlated significantly with a chemistry achievement. Chandran et al.[22] investigated the role of fluid intelligence in a sample of 11th-grade students: they found moderate positive correlations with chemistry performance (measured in terms of laboratory skills) and with acquired knowledge. However, this evidence is controversial. In fact, other authors[26] found weak and not significant correlation between fluid intelligence, visuospatial skills, and cognitive processes' speed with students' performance in an organic chemistry test; conversely, they found significant correlation with WM. The inconsistency probably comes from the fact that these studies use different cognitive tasks, which may engage various domain-general cognitive processes in differential ways.

This brief overview of the available investigations concerning the relationship between chemistry and domain-general cognitive processes highlights the fact that the role of cognitive processes differs significantly, depending on the topic and type of task. For example, evidence concerning physical chemistry problems[30,35] reports higher involvement of calculation skills as compared to other domain-general cognitive processes. The articulation of chemistry in different sub-domains with different cognitive needs complicates the study of the relationships between certain tasks and specific cognitive processes. Two domain-general cognitive processes (visuospatial skills and working memory) emerge as the most studied processes in relationship to different aspects of the chemistry discipline: the former is mainly explored in relation to students' ability to deal with the sub-microscopic level of reality; the latter is mainly explored in relation to problem-solving abilities. The present study contributes filling a gap: in fact, prior research has established a positive correlation between the WM and chemistry problem solving, but the role of WM extends beyond the mere maintenance of information during the task execution. In fact, WM plays a crucial role in *theoretical understanding*, which requires the ability to form mental representations (e.g., of molecular structures) that place a significant cognitive load on WM.

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1 Cognitive Flexibility: refers to the ability to change perspectives or approaches to a problem, flexibly adjusting to new demands, rules, or priorities (e.g. when switching between tasks).[11]

2 Visual switching task: participants are required to match an image displayed at the top of the screen with one of two alternative images in the lower corners. At the start of each trial, they receive a verbal cue specifying the criteria to be used for the matching task (e.g., color, shape).

1.2 Visualisation tools and chemistry learning: static pictures versus dynamic representations

Theoretical understanding of chemical issues, such as chirality, structural isomery, etc., requires students to generate mental representations or visualisations of entities belonging to the sub-microscopic level, and/or the mental ability to translate 2D projections into 3D molecular images. Chemistry students who are comfortable with the multi-level chemical thought and/or students equipped with good visuospatial skills have better learning outcomes as compared to those with lower visuospatial skills or less abstraction abilities.[2,9,24,47,48] It has been demonstrated that student understanding can be supported via the introduction of visualization tools.[49,50] Consequently, it is reasonable to expect that students with low visuospatial skills may benefit particularly from the introduction of such tools.

The term "visualization tool" is not defined unambiguously in the literature. For some authors, it designates various types of visual instruments that can support the teacher's explanation such as physical model of particles (e.g., ball-and-stick models), fixed or dynamic/animated computer simulations or softwares that allow students to actively generate drawing, etc.[51] However, other authors[52] apply a narrower definition, that restricts visual instruments to "any virtual environment that represents dynamic interactions of sub-microscopic (or subatomic) phenomena". In addition, thanks to technology development, immersive virtual reality is now included among the multiple visual tools that teachers may use in the classroom,[53] according to the widespread belief that it promotes chemical understanding. This tool allows students to interact actively with 3D molecular representations, e.g. to grab and rotate molecules, and even to visualize sub-microscopical dynamic processes. Leaving aside the discussion about the didactic effectiveness of virtual reality, we wish to focus on the difference between static representations of molecules and/or molecular assemblies versus dynamic representations of the same systems (e.g. rotating images that allows users to view molecular or supramolecular structures from multiple perspectives, thus sparing the effort of mentally imagining the rotating structure). One point of debate concerns whether dynamic display is more or less effective than the static one in promoting chemistry understanding.

The literature reports contrasting evidence on this issue.[52,54] Some studies suggest that dynamic visualisations have positive effects on students' learning outcomes across multiple scientific disciplines as, for example, they support learners in mentally visualizing chemical changes at the molecular level.[49,50,55] The effect of dynamic visualisation was proven stronger in geology, biology and medicine science as compared to physics, chemistry, technology, engineering, and mathematics.[54,56] A meta-analysis of these results[56] showed a medium significant positive effect of dynamic images in chemistry. Regardless the discipline, the analysis showed a stronger effect of dynamic visualization in the absence of additional textual information or in the presence of oral comments (that load on students' auditory system, thus lightening the visuospatial components). Nevertheless, other evidence goes the opposite direction, suggesting that dynamic visualization does not always outperform static representations and may even hinder learning.[57,58] These conflicting findings about the effectiveness of dynamic visualization might be explained by considering the differential cognitive load implied by the static and dynamic display mode: in fact, videos oblige students to split their attention between auditory and visual information and to integrate them. Furthermore, dynamic representations (e.g., GIF animations) are transient, and, in some cases, there is no possibility to rewatch them. This prevents students from reviewing pieces of information conveyed in this way and potentially increases the cognitive load.[57]

Other evidence in favour of animations as useful tools in chemical education come from Ardac and Akaygun,[49] who assessed a sample of 8th-grade children, engaged in studying chemical changes at the sub-microscopic level.[49,50,52] Three conditions were compared: dynamic-individual (students view the animation on their personal computer); dynamic-collective (the animation were projected to the whole class); static-collective (no animations, but static pictures projected to the whole class). A meaningful difference between static versus dynamic visual modes was found: students in the static condition performed worse, whereas students in the dynamic group (both individual and collective) were more accurate. This suggests that animations promote an integrated understanding of phenomena.[49] Furthermore, such positive effect was higher among students in the dynamic-individual condition. However, Kelly and Jones[59] reported that molecular animations alone are insufficient to promote effective learning of the dissolution process, based on students' ability to transfer concepts learned from molecular animations. The instructor's guidance is essential for helping students to create and integrate the multiple pieces of information and achieve deep understanding.

In summary, literature findings suggests that dynamic visualization tools may contribute promoting students' understanding of chemical topics. However, these findings are not always consistent, as the effectiveness of these tools seems to depend on individuals' differences (e.g. gender and educational level[54]) and to vary between different chemistry domains. Hence, investigating the cognitive aspects in parallel with teorethical ones might provide deeper insight on the causes of such differences.

In addition, in the chemistry educational context, dynamic visualization tools have been mainly applied to the topics of chemical changes and sub-microscopic phenomena. Considerably less evidence is available on the impact of dynamic representation of 3D molecular structures on students' understanding of structural differences. For example, do dynamic representations of molecules rotating along their axis promote students' understanding of chirality or isomery or molecular geometry? Or is there a correlation between the effectiveness of such tools and individual cognitive profiles (visuospatial ability, working memory ability, and fluid intelligence)?

Based on these considerations, we engaged in the present study that focuses on the relationship between the use of rotating 3D supramolecular models and domain-general cognitive processes in chemistry learning. Our research questions were the following:

RQ 1: To what extent does the use of dynamic representations of molecular and supramolecular structures promote students' theoretical understanding of chemistry structural aspects?

RQ 2: What is the impact of using dynamic tools on the chemistry learning achievement of students with lower visuospatial working memory capacity?

RQ 3: Does the condition (static vs. dynamic) moderate the relationship between visuospatial working memory capacity and chemistry learning achievement?

2 Methodology

2.1 Participants

The sample included 205 students (115 static vs. 90 dynamic conditions). We report a more detailed description in the table below (Table 1).

All 205 students were enrolled in a scientific degree course that included at least one general chemistry exam in its curriculum: Agro-engineering (N = 7); Biotechnology (N = 29); Chemistry (N = 28); Pharmacy (N = 28); Biology (N = 60); Natural Science (class A N = 33 and class B N = 19).

Table 1: Gender distribution, mean age and university affiliation of the sample involved in the present investigation.

	Static condition				Dynamic condition			
	Male	**Female**	**M_{age} (SD)**	**University**	**Male**	**Female**	**M_{age} (SD)**	**University**
Chemistry learning and cognitive processes assessment (N = 205)	50	65	19.44 (1.63)	Palermo N = 36 (31.3 %) Turin N = 79 (68.7 %)	30	60	19.04 (1.57)	Palermo N = 56 (62.2 %) Turin N = 34 (37.8 %)

2.2 Procedure and research design

The established design consists of two parts, which were both administered collectively (Figure 1). Data collection occurred between October and December 2024.

Phase 1 focuses on the achievement of chemistry learning objectives in the static versus dynamic condition. A chemistry learning assessment was done on the control group (exposed to static pictures of liquid crystal structures) and the experimental group (exposed to GIF animations). This variation addresses RQ1, allowing to assess impact of dynamic representations on students' understanding of chemistry structural aspects.

Phase 2 focuses on a cognitive assessment. Verbal and visuospatial working memory, as well as estimated intelligence quotient (IQ) were measured in both the control and the experimental group. This phase addresses RQ2 (by assessing the effect of dynamic and static representations on students with lower working memory capacity) and RQ3 (by testing if the representational format moderates the relationship between visuospatial working memory and chemistry learning achievement).

These two phases were structured as follows:

– *Phase 1 – Assessment of chemistry learning abilities (approximately 1 h):*

Chemistry learning ability has been assessed as follows: students were asked to perform a chemistry task (described below), and to fulfil a short questionnaire including few personal details (age, gender, and type of degree course). The chemistry learning task was assessed in the static versus dynamic condition, based on the type of visualisation tool implemented. Each class was randomly assigned to one of the two conditions, to ensure that all students within a given class were exposed to the same visualization mode under controlled and comparable conditions, we opted for a between-class randomization, assigning whole classes to either the static or dynamic condition: Agro-engineering (static); Biotechnology (static); Chemistry (dynamic); Pharmacy (dynamic); Biology (static); Natural Science (class A static and class B dynamic).

– *Phase 2 – Assessment of WM and visuospatial abilities (approximately 1 h):*

Students were asked to perform two WM tasks (a verbal and a visuospatial WM task) and were assessed with the Cattell's fluid intelligence test, scale 2[60] measuring students' estimated IQ (intelligence quotient). The

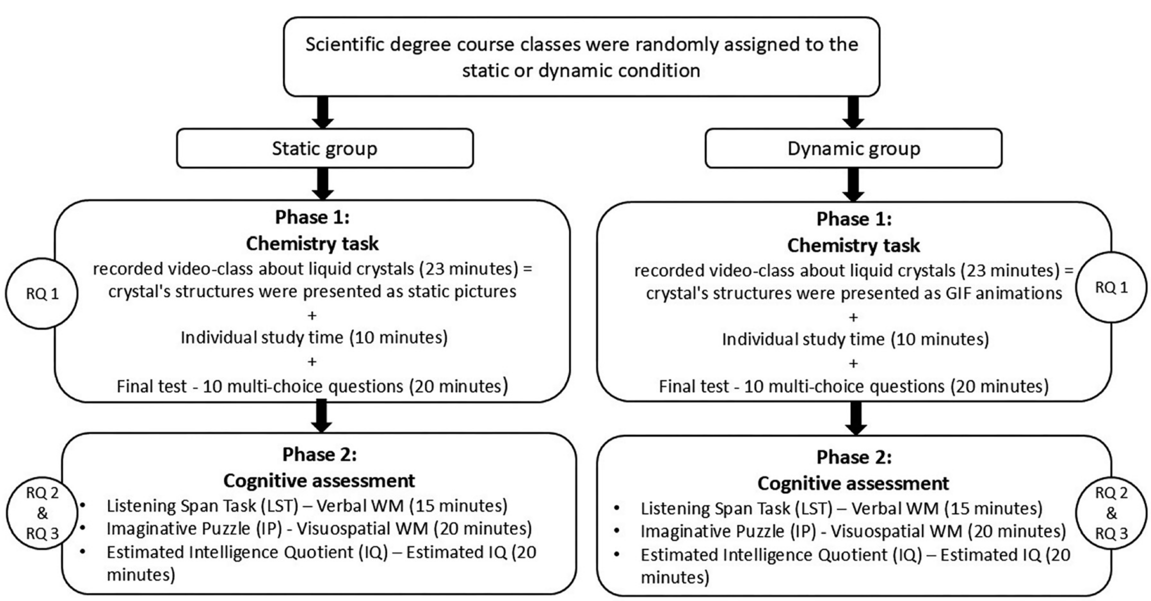

Figure 1: Schematic representation of the study design. Classes were randomly assigned to the static or dynamic visualization condition.

administration of the tasks was implemented thanks to a learning management system platform (Moodle). Students were assessed in person, but they performed all the tasks using their smart-phone or tablet or PC.

2.3 Instruments

2.3.1 Chemistry task (CT)

The CT was designed *ad hoc* for the present research, and its structure resembled the Learning Task included in the Italian standardized tool or the assessment of study method among undergraduates.[61] The CT assesses students' chemistry learning ability and understanding: students first watch a recorded video-class about liquid crystals (23 min); then, they are given 10 min for individual revision (based on the lecture's slides and their notes); finally, they are required to answer a short test on the same topic (10 multi-choice questions – 5 textual and 5 visual; see Table S1, in Supplementary Material), administered online through the Qualtrics platform. Multi-choice questions are classified as textual or visual based on the format of the answer choices: textual questions rely on text-based options, while visual questions rely on image-based options. The video-recorded lecture covers history, structural properties, and technological applications of liquid crystals (e.g., liquid crystal displays). The content was designed to be accessible to anyone (i.e. its comprehension does not require prior specialized chemistry knowledge, and students are expected to rely solely on the basic chemistry background acquired during their upper secondary education). A detailed description of the task can be found in De Vita et al.,[62] although here we applied two variants: the video-class was assessed in either of two distinct conditions (static vs. dynamic); we removed the teacher's frame, so that explanation could be heard without seeing the speaker. The static condition corresponds to showing liquid crystal's structures as static pictures; the same pictures were reported in the slides. The dynamic condition corresponds to showing liquid crystal's structures as animations (i.e. undergoing a 360° rotation around their vertical axis). Examples of the smectic C supramolecular representation in both the static and dynamic versions are provided to help readers understand the differences between the two conditions.[3] The lectures' slides made available to the students did not include animations: all structures were presented as static pictures. Evaluation was done as follows: the final score was the sum of correct answers (maximum score = 10), whereas missing answers were counted as errors. The number of correct textual and visual responses was also assessed separately (maximum score = 5 for both cases). Moreover, regardless of the type of response, the 10 questions were classified as either factual or conceptual. Factual questions mainly rely on the recall of information; conceptual questions require students to carry out further reasoning in order to reach a deep-level understanding. The number of correct factual (maximum score = 4) and conceptual (maximum score = 6) questions was calculated too. Their score was translated into percentage so the two measures could be compared (see below).

$$\text{Factual} = \frac{\text{nr of factual questions correct}}{4} \times 100$$

$$\text{Conceptual} = \frac{\text{nr of conceptual questions correct}}{6} \times 100$$

2.3.2 Listening span task (LST) – verbal WM

The listening span task – LST[63] was implemented for assessing students' verbal WM. Students listened to and were asked to decide about the truthfulness of a number of statements (from two up to six sentences), and after each set of sentences they had to recall the last word of each statement (see Table S2, in Supplementary Material). This task assesses students' ability to maintain and manipulate (update) verbal information. The final score was obtained by summing up the number of words recalled in the proper order of presentation (maximum score = 20).

3 https://osf.io/c4unm/overview?view_only=ebfde82f329d4c4d9d05dbb19ad39a46.

2.3.3 Imaginative puzzle (IP) – visuospatial WM

Imaginative puzzle – IP[63,64] evaluates students' visuospatial WM. It specifically targets students' ability to actively hold and manipulate visuospatial information, rather than visuospatial ability per se. Moreover, unlike other established tasks, the IP is more suitable for collective setting, as it could be easily administered to the whole class via the Moodle platform. This task consisted of 27 items organized in nine levels (from level 2 to level 10, with three tasks per level). Students were required to mentally reassemble a picture of a familiar object that was shattered in multiple pieces (see Table S2, in Supplementary Material). The final score was measured by summing up the level-number of the most three complex levels successfully completed by the student (maximum score = 30).

2.3.4 Estimated intelligence quotient (estimated IQ)

Cattell's fluid intelligence scale[60] provides an estimated intelligent quotient (IQ) of each student who joined the investigation. The manual consists of two different scales (part 1 and part 2) and allows estimating IQ score, no matter if both parts or only one out of two parts are administered, thanks to conversion tables. We administered only part 2. The assessment relies on four different types of problems: *Series* (12 items, 3 min, maximum score = 12); *Classification* (12 items, 3 min, maximum score = 12); *Matrix* (12 items, 3 min, maximum score = 12); Analogies (9 items, 3 min, maximum score = 9). Students are asked to solve as many problems as possible for each set, in a limited-time range (see Table S2, in Supplementary Material). The final score was obtained by counting the number of right answers (maximum score = 45). Then it was 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 (α = 0.72).

2.4 Data analysis

Data analysis was computed with the Jamovi Project Version 2.3[65] and R Studio.[66] First, we analysed and compared students' performance in the CT in the two conditions (static vs. dynamic). We calculated mean and standard deviation of both the total and the partial scores (textual and visual as well as factual and conceptual questions). Additionally, descriptive statistics of the students' performance in the cognitive tasks (LST, IP, and estimated IQ) were calculated. A comparison was made between the two groups (static vs. dynamic) by using the non-parametric alternatives tests to the Student's *t*-test (Mann-Whitney U test), based on the non-normality of the data distribution, as indicated by a significant Shapiro-Wilk test result.

Second, we assessed possible differences between static and dynamic conditions performance, based on students' visuospatial WM ability. The 205 students were splitted into three groups, according to their performance at the IP task (low: IP $\leq$20; medium: 21 $\geq$ IP $\geq$26; high: IP $\geq$27) and we computed two separate one-way non-parametric ANOVAs (Kruskal-Wallis), for the static and the dynamic conditions, respectively. Then, we investigated the differential performance of these three groups in the textual and visual questions. The same comparison was made for the factual and the conceptual questions. In this last case, the percentages of accuracy were compared, due to the different number of factual versus conceptual questions (4 vs. 6).

Finally, we computed a step-wise regression analysis on the (static + dynamic) groups, using the total score of the chemistry task as dependent variable, and the cognitive tasks as well as the type of condition (static vs. dynamic) as predictors. The interactions "IP score*condition" and "Estimated IQ score*condition" were also included in the model, so to get insights about the differential involvement of the visuospatial WM and the general cognitive ability in the dynamic condition.

3 Results

3.1 Students' performance at the chemistry task (CT) in static versus dynamic conditions: exploring the individual cognitive processes involved

The effect of dynamic representations of liquid crystal structures on students' theoretical understanding (RQ1) was assessed by exposing students to the same video-lecture, either in the static or the dynamic conditions. Descriptive statistics relative to this first investigation are reported in Table 2 (lines 1–6). Data suggests that students' performance in the chemistry task (CT) shows no significant difference between static versus dynamic conditions. In particular, no difference emerges in the total score. Moreover, the analysis across the four partial scores (textual, visual, factual, and conceptual) does not highlight specific differences.

As our study aimed at integrating the investigation on disciplinary learning processes with the study of the cognitive functions involved in chemistry learning (RQ 2 and RQ3), the same students' population was involved in a further assessment focused on three cognitive tasks (listening span task, imaginative puzzle and estimated intelligence quotient). The results of this further investigation are reported in Table 2 (lines 7–9).

These results highlight a significantly worse performance of the dynamic group as compared to the static one across all three cognitive tasks, thus suggesting that – despite the nearly equivalent performance on the chemistry task – the group exposed to the dynamic condition shows an impact on the individual cognitive functions, that was somewhat compensated for, during the chemistry task. In order to get further clues for interpreting these results, we computed two separated correlational analyses (one for the static and one for the dynamic group). The results confirmed that correlations between students' performance on the chemistry tasks and cognitive measures were different across the two experimental conditions (see Table 3).

It is interesting to note that the total CT score for the static group shows a significant correlation with the IP task, which measures visuospatial working memory (the correlation is moderate and positive), and with the estimated IQ (the correlation is low and positive). On the other hand, the total CT score of the dynamic group correlates significantly with the LST task that measures verbal WM (correlation is low and positive) and to the estimated IQ score (correlation is moderate and positive). This suggests that visuospatial WM become less relevant in the dynamic condition, as if students with lower visuospatial WM ability were somehow able to compensate for this limitation when exposed to the dynamic condition.

As we were especially interested in the impact of dynamic tools on chemistry learning achievement among students with lower visuospatial WM capacity (RQ2), a further analysis was performed, concerning possible differences on the partial scores of the chemistry tasks between static and dynamic groups, based on students'

Table 2: Mean (M), standard deviation (SD), median and non-parametric comparisons of students' performances in the two conditions (static vs. dynamic).

		Static (N = 115)			Dynamic (N = 90)			Non-parametric comparisons	
		M	SD	Median	*M*	SD	Median	Mann-Whitney's U	Effect size
Chemistry task (CT)	Total	5.99	1.90	6	5.94	1.86	6	5,147	0.947
	Textual	3.51	1.05	4	3.46	1.12	4	5,106	0.866
	Visual	2.48	1.33	2	2.49	1.27	2	5,157	0.965
	Factual	70.43 %	25.34 %	75 %	69.17 %	23.72 %	75 %	4,935	0.549
	Conceptual	52.90 %	21.99 %	50 %	52.96 %	22.84 %	50 %	5,122	0.898
	Time (in seconds)	454	110	439	458	106	450	4,976	0.638
Cognitive tasks	LST – verbal WM	17.0	2.61	17	15.9	3.20	16.50	4,130*	0.012
	IP – visual WM	24.0	3.62	25	22.5	4.10	22	4,025**	0.006
	Estimated IQ score	109.3	12.95	111	103.2	13.01	103	3,842**	0.002

*$p < 0.05$; **$p < 0.01$.

Table 3: Correlational analysis results (Spearman's rho) in the static and dynamic group.

	Static (N = 115)				Dynamic (N = 90)			
	1	2	3	4	1	2	3	4
1. LST (verbal WM)	1				1			
2. IP (visuospatial WM)	0.07	1			0.11	1		
3. Estimated IQ	−0.06	0.44***	1		0.13	0.41***	1	
4. CT (total score)	0.16	0.49***	0.27**	1	0.27**	0.21	0.42***	1

**$p < 0.010$; ***$p < 0.001$. LST, listening span test (verbal WM task); IP, imaginative puzzle (visuospatial WM task); Estimated IQ, estimation of intelligence quotient; CT, chemistry task.

visuospatial WM ability. Therefore, students were divided in three groups, according to their performance at the IP task, as described in the Data Analysis section (low; medium; high). Their performance on the textual, visual, factual and conceptual questions was compared across the three groups (see Table 4), through several separated one-way non-parametric ANOVAs (Kruskal-Wallis).

The analyses pointed out a significant main effect of the variable "imaginative puzzle (IP) group". More in details, concerning the static group, a significant difference between IP groups was found in the accuracy in the textual questions (Low IP[a] < Medium IP[a,b] < High IP[b]), in the visual questions (Low IP[a] < Medium IP[a] < High IP[b]), and in the conceptual questions (Low IP[a] < Medium IP[a] < High IP[b]). Conversely, concerning the dynamic group, a significant difference was observed between the IP groups, only in the factual questions (Low IP[a] < Medium IP[a,b] < High IP[b]). These findings confirm that visuospatial WM influences differentially the chemistry task performance depending on the experimental condition (static vs. dynamic).

3.2 Students' performance at the chemistry task (CT) in static versus dynamic conditions: regression analysis

Finally, in order to investigate whether the experimental condition (static vs. dynamic) moderates the relationship between visuospatial WM and chemistry task (RQ3), we implemented a step-wise regression analysis by using the total score at the chemistry task as the dependent variable, and the cognitive tasks and the type of condition (static vs. dynamic) as predictors. Given the results of the correlational analyses, the interactions "IP

Table 4: Results of the one-way non-parametric ANOVAs (Kruskal-Wallis) comparing the three IP groups' performances in the partial scores of the chemistry task.

	Low IP (N = 27)		Medium IP (N = 52)		High IP (N = 34)			
	M	SD	*M*	SD	*M*	SD	*F*	*p*
Static (N = 115)								
Textual	3.11	0.89	3.44	1.06	3.92	1.03	**6.53****	0.004
Visual	1.85	1.26	2.31	1.25	3.19	1.19	**6.93****	0.003
Factual	60.19 %	25.25 %	71.63 %	25.74 %	76.39 %	23.10 %	3.23	0.051
Conceptual	42.59 %	19.79 %	48.08 %	19.71 %	67.59 %	19.50 %	**11.1*****	<0.001
	Low IP (N = 36)		Medium IP (N = 36)		High IP (N = 22)			
Dynamic (N = 90)								
Textual	3.29	0.94	3.38	1.28	3.82	1.10	2.30	0.119
Visual	2.32	1.20	2.26	1.19	3.09	1.38	3.05	0.067
Factual	63.97 %	22.35 %	67.65 %	25.25 %	79.55 %	21.32 %	**6.86****	0.003
Conceptual	50.98 %	20.08 %	49.02 %	23.19 %	62.12 %	24.76 %	2.32	0.114

**$p < 0.010$; ***$p < 0.001$. IP, imaginative puzzle (visuospatial WM task). Bold values indicate statistically significant differences.

score*condition" and "Estimated IQ score*condition" were also included in the model. The results are reported in Table 5 and the interaction diagrams are shown in Figure 2.

The regression analysis shows that both verbal WM and the estimated IQ score are significant predictors, whereas the visuospatial WM is not. On the other hand, a significant relationship between the visuospatial WM and the static or dynamic condition is evident: low IP score associates with lower performance in the chemistry task only in the static condition.

4 Discussion

The present investigation had three aims: investigating whether the dynamic representation of molecular structure promotes students' theoretical understanding (RQ 1); exploring the impact of dynamic representations on students with low visuospatial WM capacity (RQ 2); and, testing whether the condition (static vs. dynamic) moderates the relationship between visuospatial WM e chemistry learning (RQ 3). In order to acquire information about these issues, we carried out an investigation that combines chemistry and cognitive tasks. In fact, we first assessed a sample of 205 Italian undergraduates with a chemistry learning task in two different conditions (static vs. dynamic). Then, we explored how students' performance in the chemistry learning tasks was related to WM components (verbal and visuospatial) and to general cognitive abilities, through the executions of targeted cognitive tasks.

Unexpectedly, our findings show the absence of significant differences between the two experimental conditions (static vs. dynamic) in the chemistry task. The existing literature concerning the implementation of dynamic visualisation tools presents conflicting evidence. According to a recent meta-analysis[54] dynamic representations can have positive effects on science learning (chemistry included). On the other hand, Castro-Alonso et al.[67] found that coping with dynamic visualisations (such as video, animations or augmented reality) is complex from a cognitive point of view, since this material could result too fleeting and difficult to follow. Furthermore, students could self-perceive a high cognitive load when they deal with these materials.[68] Recently, an insightful reflection on the implementation of the visualization tools within the framework of Cognitive Load Theory, emphasizes that the design of effective instruments should be grounded in its core principles.[57] In the light of these remarks, and in order to find a useful clue for interpreting our findings on the chemistry task, we explored students cognitive abilities either under the static or the dynamic condition. Our findings offer additional empirical evidence to the ongoing debate: data concerning the cognitive tasks show that the dynamic group performed significantly worse in each of the three cognitive tasks (LST, IP and estimated IQ). Interestingly, the lower performance of the dynamic group across all three cognitive tasks did not translate into poorer chemistry learning outcomes, which remained comparable to those of the static group. This result is crucial, as previous

Table 5: Results of the regression analysis examining the predictive role of the cognitive processes (verbal WM, visuospatial WM, and fluid intelligence – estimated IQ), of the experimental condition (static vs. dynamic), and of their interaction, on the total score of the chemistry task.

Effect	Estimate	SE	95 % CI		*T* value	*p*
			Low	High		
(Intercept)	6.175	0.186	5.81	6.54	33.1	<0.001
LST – verbal WM	**0.088**	**0.042**	**0.01**	**0.17**	**2.12***	**0.035**
IP – visual WM	−0.006	0.049	−0.58	−0.10	0.09	0.901
Estimated IQ score	**0.054**	**0.015**	**0.02**	**0.08**	**3.48*****	**<0.001**
Group (static vs. dynamic)	−0.419	0.249	−0.91	0.07	−1.68	0.094
IP*group	**0.212**	**0.069**	**0.07**	**0.35**	**3.06****	**0.003**
Estimated IQ*group	−0.034	0.021	−0.08	0.01	−1.64	0.104
	R^2adj = 0.1895, $F(6, 198)$ = 8.949, $p < 0.001$					

*$p < 0.05$; **$p < 0.010$; ***$p < 0.001$. Bold values indicate statistically significant differences.

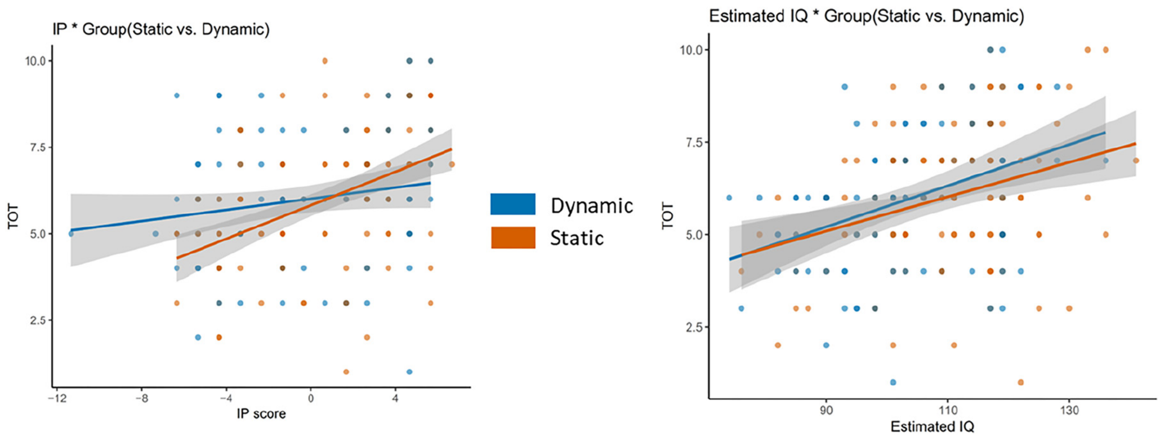

Figure 2: Interaction plots: on the right we can observe the interaction between the IP score and the condition (static vs. dynamic); whereas on the left side is reported the not significant interaction between estimated IQ and condition.

studies[62] demonstrated a significant correlation between cognitive tasks and students' performance at the chemistry task. The correlational analysis between students' accuracy in the chemistry learning task and the cognitive tasks highlights that the estimated IQ relates significantly to chemistry learning, and the relationship is stronger in the dynamic group. This clearly indicates that dealing with dynamic representations correlates with fluid intelligence abilities. This result is consistent with current literature[57,67,68] which acknowledges that higher cognitive load is associated with dynamic visualisations compared to the static ones. Moreover, our analysis points out that the CT task performance correlates moderately with visuospatial WM components in the static group, whereas it is weakly related to the verbal components in the dynamic group. The results in the static group are consistent with literature evidence[20,23,62,69] showing that visuospatial WM components relates to students' accuracy in a chemistry learning task. On the other hand, the correlational results in the dynamic group highlight that students' accuracy is not correlated to visuospatial WM; conversely, it correlates with verbal WM. The overall results suggest that students in the dynamic group have to deal with complex visual information as well as with verbal one: this placed a greater load on their verbal WM compared to the static group. However, the learning outcomes in the dynamic condition are more related to students' fluid intelligence abilities, rather than to visuospatial WM component. This is probably due to the complexity of the task.

In line with these results, our subsequent investigation focussed on establishing the specific relationship between the visuospatial WM component and the partial scores obtained on the chemistry task across the two experimental conditions (static vs. dynamic). The comparison between the performance of students with low, medium, and high visuospatial WM shows that differences in the partial scores for the chemistry task between the three groups are primarily evident in the static condition (Table 4). This suggests that students in the dynamic condition, (and especially those with low visuospatial WM ability), are able to compensate for their weaknesses. Furthermore, in the dynamic condition, we found a significant difference in the scores of factual questions (that require the mere retrieval of information), whereas the scores of conceptual questions (that require further elaboration) were comparable. This apparent contradiction can be solved by considering that factual questions demand the instantaneous manipulation and integration of both verbal and visuospatial information, thus generating an overload of WM components. The animations used in the dynamic condition facilitate the construction of 3D mental representations of liquid crystal structures: this reduces the overload of visuospatial WM and leaves more space for a more strategic managing of the wealth of information conveyed by the video lecture. As a result, even students with low visuospatial WM ability manage to achieve deep understanding and perform comparably to their peers with high visuospatial WM, in the conceptual questions. This mechanism suggests that dynamic animations may be a valuable resource to promote chemistry learning among students with low visuospatial WM ability.

Finally, a step-wise regression analysis was computed (Table 5) to identify which predictors are significant in terms of success in the chemistry task (RQ3). Our result shows that – in both static and dynamic conditions – students with higher verbal WM scores performed better; likewise, students with higher estimated IQ scores performed better in both conditions. This suggest that verbal WM as well as fluid intelligence play a consistent predictive role in chemistry task performance, regardless the type of experimental condition (static vs. dynamic). Furthermore, the interaction effect "IP score*condition" confirm that the introduction of dynamic animations may support students with low visuospatial WM ability in understanding a chemistry topic that asks to deal with the sub-microscopic level of reality. On the other hand, the interaction "Estimated IQ*condition" resulted not significant, even if the plots shows that the relationship between fluid intelligence and chemistry task performance is slightly stronger in the dynamic group. Overall, this final analysis confirms that dealing with dynamic animations loads on fluid intelligence abilities.[57,67,68] At the same time, it suggests that these tools may be supportive to students with lower visuospatial WM skills.

5 Conclusions and future developments

In summary, the present research contributes to achieve a better understanding of the relationship between chemistry learning and WM components (verbal and visuospatial), as well as about the effects of using static versus dynamic visual tools to explain sub-microscopical chemistry concepts in students. Our findings provide additional evidence to the ongoing debate on the effectiveness of dynamic representation in chemistry education. In particular, we were interested in understanding whether the use of dynamic representations of molecular and supramolecular structures promote students' theoretical understanding of chemistry structural aspects (RQ1). Our data suggest that the use of such tools can be a valuable resource for learning, particularly for those students exhibiting weaknesses in their domain-general abilities (verbal and visuospatial WM, and fluid intelligence). Furthermore, the introduction of dynamic visualizations appears to have an impact on the relationship between chemistry achievements and visuospatial WM (RQ2 and RQ3). Notably, students with low visuospatial WM in the dynamic condition performed comparably to their peers with high visuospatial WM in textual, visual and conceptual questions. Overall, our data concluded that dynamic condition moderate the relationship between visuospatial WM and chemistry achievement.

Despite the intriguing insights offered by this work, we would like to acknowledge its limitations. First, we did not collect measures of self-perceived cognitive load. Future research should include such measures to determine whether students exposed to the dynamic condition report higher levels of self-perceived cognitive load. Second, the present investigation was restricted to a comparison between static versus dynamic visualisation tools. This choice aimed at testing a visualization tool that could be easily implemented in an educational or school setting. Nevertheless, more structured and interactive visualization tools are available (e.g., the manipulation of 3D computer-based models on a smartphone or computer screen, or the use of immersive virtual reality). Future research should investigate the effects of such tools on learning.

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Research ethics: The present study protocol is part of the research project was submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023).
Informed consent: Informed consent was obtained from all individuals included in this study, or their legal guardians or wards.
Author contributions: All the authors conceptualized 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. Francesca De Vita and Elena Ghibaudi wrote the first draft of the manuscript, and the subsequent revisions. All authors reviewed and approved the final manuscript.
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