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Verbal and Visuospatial components of Working Memory and Chemistry Learning among Undergraduate Students with and without Specific Learning Disabilities (SLDs)

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Francesca De Vita Palermo, December, 2025

Summary

This doctoral research investigates how verbal and visuospatial components of Working Memory (WM) contribute to chemistry learning, with particular attention to students with and without Specific Learning Disabilities (SLDs). Building on Johnstone's triplet model of chemical representation—macroscopic, sub-microscopic, and symbolic—this work explores how the two domain-specific components of WM support students' ability to understand a chemistry topic. Furthermore, it investigates whether the implementation of dynamic visualization tools (short animation) facilitates the comprehension during a chemistry learning task.

We designed an *ad hoc* chemistry learning task focused on liquid crystals, and we implemented it through six empirical studies to assess performance under various conditions. The first two studies, involving students with Typical Development (TD) students, revealed that visuospatial WM is more strongly associated with success in chemistry tasks than verbal WM. Students performed better in text-based questions than in visual ones, but those with higher visuospatial WM scores achieved greater accuracy, particularly when deep conceptual understanding and mental manipulation of molecular structures were required.

The third and fourth studies extended this analysis to students with SLDs. Results showed that, although these students required more time to complete the chemistry task and scored lower in verbal WM. Their overall accuracy was comparable to that of peers with TD who were matched for IQ and visuospatial WM. The findings confirm that students with SLDs face greater difficulty with text-based information but they can perform effectively when tasks rely more on visuospatial reasoning. Furthermore, an interesting result that emerged from these findings is that providing them with more time is necessary, but in some cases could be no sufficient. For those who manifest weaknesses in visuospatial WM, it is essential to equip them with appropriate accommodations that can support their verbal and visuospatial WM.

The fifth and sixth studies examined the impact of visualization tools by comparing static (picture) and dynamic (short, animated video) representations of molecular structures. Among students with TD, dynamic animations did not significantly enhance performance overall, but it appeared to benefit those with lower visuospatial WM capacity. However, students with SLDs did not show similar gains: exposure to dynamic animations tended to increase cognitive load, leading

to lower accuracy. These outcomes suggest that passive dynamic visualizations may not effectively support learning for students with SLDs and could even hinder comprehension if verbal and visual information are presented simultaneously. Collectively, this research examines in depth how verbal and visuospatial WM components are related to chemistry learning and offers important implications for inclusive education. Visuospatial WM emerges as a key factor underpinning students' ability to engage with sub-microscopic chemical representations. For learners with SLDs, instructional design should minimize cognitive overload by simplifying visual information, sequencing verbal and visual input, and providing additional time. The findings highlight the need for further research on interactive visualization tools that actively engage learners. In order to determine whether the introduction of such tools may produce significant advantages in learning outcomes for both students with and without SLDs.

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Introduction

The study of how students learn and understand scientific concepts has long been a central concern in educational psychology. Chemistry represents a uniquely challenging domain due to the high degree of abstraction required to move between macroscopic, sub-microscopic, and symbolic representations of matter. Mastery in this discipline requires not only the acquisition of factual knowledge but also the ability to mentally manipulate representations of not directly observable elements, such as atoms, molecules, and their interactions. Such demands inevitably place a heavy burden on Working Memory (WM), the cognitive system responsible for the temporary storage and manipulation of verbal and visuospatial information.

Previous research has demonstrated the relevance of WM capacity and efficiency for performance in complex learning tasks, including mathematics and science. Numerous studies investigated the relationship between WM and chemistry, and they all agree on its pivotal role. However, less is known about how the two WM components (verbal and visuospatial) contribute to chemistry learning, a domain in which both verbal and visuospatial processing are arguably essential. Moreover, the literature rarely considers how these processes unfold in students with Specific Learning Disabilities (SLDs), such as dyslexia, dysgraphia, dysorthography, or dyscalculia, despite the growing presence of students with SLDs in higher education. This constitutes a critical gap in research, as SLDs are known to affect academic performance in ways that may extend beyond literacy and numeracy. Another key challenge in chemistry education concerns the design of effective instructional materials. Traditional teaching methods often rely on static images or verbal explanations, which may fail to adequately support students in visualizing the dynamic and three-dimensional nature of molecular structures. The integration of dynamic visualization tools, such as short animations or rotating molecular models, has been proposed here as a device to reduce cognitive load and facilitate comprehension. While some evidence supports the benefits of such tools, others focus the attention on the cognitive burden of dealing with these complex visualization tools. Finally, their impact on learners with SLDs has yet to be systematically investigated.

The present doctoral research addresses these gaps by pursuing two main objectives. Firstly, it examines the relationship between verbal and visuospatial WM components and chemistry learning outcomes in university students with and without SLDs. Secondly, it investigates whether the introduction of short video-based animations of molecular structures enhances students' understanding of a chemistry topic that requires the manipulation of sub-microscopic representations of matter. To these ends, an *ad hoc* chemistry learning task was developed, consisting of a brief video lecture on liquid crystals followed by a final comprehension test. Measures of verbal WM, visuospatial WM, and estimated IQ were also collected to explore how these cognitive factors interact with students' performance in the task.

The thesis is structured into five chapters. Chapter 1 provides a literature review that situates chemistry education within the framework of cognitive psychology, with a focus on cognitive processes underlying the learning of scientific concepts. Chapter 2 introduces the main characteristics of SLDs, highlights the challenges faced by students with SLDs in higher education, and reviews the specific difficulties encountered in science learning. Chapters 3 and 4 present the empirical studies: Chapter 3 reports four studies exploring the relationship between WM components and chemistry learning in students with and without SLDs, while Chapter 4 reports two studies investigating the effects of introducing dynamic visualizations on chemistry learning outcomes in the same populations. Finally, Chapter 5 summarizes and integrates the findings of the six studies, discussing their implications for both cognitive psychology and educational practice, and outlining directions for future research.

Chapter 1: Cognitive processes involved in chemistry learning

1.1 Introduction

The act of learning entails the constant effort to integrate new information with previous knowledge, stored in the long-term memory, and it can be incidental or intentional. Both require an active role of the students, but they differ for the way the new information has been presented. Incidental learning happens naturally during activities not primarily aimed at learning, and it can occur through observation, repetition, social interaction, problem-solving, or adapting to situations. On the other hand, intentional learning occurs when individuals consciously strive to acquire and internalize new knowledge or skills through deliberate effort. In this context, we will focus on the latter, as it is the predominant form of learning in educational and school settings, regardless of grade level. We will focus on chemistry learning, and we will explore the role of the different cognitive processes involved in the understanding of this particular subject.

The need to examine in depth chemistry education gathers from the observation of the national data about science education. The OCSE Pisa report (INVALSI, 2019, 2022) showed that Italian students' performance in scientific area is significatively below the mean OCSE score. A slight improvement in students' performance can be observed (score: 468 in 2018; score: 477 in 2022) but this difference is not significative (INVALSI, 2022, p.123). Additionally, if we consider the national and international trend in the last decade (2012-2022), a significant decrease in students' performance emerges. The reason behind this entails a wide variety of factors. Focussing on the Italian context: educators struggle in promoting teaching approaches that differ from the traditional frontal class (A. Cavalli & Argentin, 2010), since the time given to science education is not enough and school laboratories are not always available. Therefore, in the Italian educational context, practical/laboratory classes are quite rare and learning scientific subjects is mostly a mere memorization of concepts and definitions leading to a lack of understanding.

Science education aims to teach students concepts and theories that can directly be applied in real life context (Bybee, 2013). This is why teaching these disciplines asks the educators to integrate the theoretical framework explanation with the practical experiences to allow a full understanding of the concepts. Through scientific disciplines, indeed, an observed phenomenon (e.g. the ball on the inclined plane) can be generalized in a specific mathematical law, applicable beyond the specific context and written using the mathematical language. Hence, every specific

law (usually based on mathematical formulas) must be read by the student not only as a mere combination of mathematical symbols but trying to understand the physical meaning within the formula. The same applies for other scientific disciplines, such as chemistry and biology. Further complexities arise from the need to deal with a variety of information (partly auditory-verbal and partly visual-spatial) alongside the increasing levels of abstraction that theoretical concepts reach as education progresses. Given all these complexities, European as well as international guidelines suggest that the most effective methodology for learning science is the Inquiry Based Learning – IBL[1] (Council National Research, 2000, 2006; European Commission, 2011; Rocard et al., 2007). Consistent with trends observed across other scientific domains, IBL has been extensively adopted within the field of chemistry education (see for example, Jegstad, 2024; Nzomo et al., 2023; Xoliyorova et al., 2024).

1.1.1 Interdisciplinary approach to chemistry education

In this context we are interested specifically in one scientific subject: chemistry. Chemistry is included in many different educational curricula, and it has also been reported in literature as a complex discipline (Chittleborough, 2014; Johnstone, 1991). Literature (Jegstad, 2024) has pointed out that using IBL practice in chemistry education can have positive effects in terms of understanding, and it can also increase students' engagement. However, implementing IBL in chemistry loads up on students' cognitive resources, and requires them to be cognitively flexible (Kang et al., 2022). Some recent neuroscience studies (Hampshire et al., 2016, 2019) demonstrated, indeed, the significant role of cognitive circuits involved in IBL. Students are challenged to constantly handle, update and integrate knowledge and information, and this encompasses persistent adjustments and modifications of the dynamic brain networks that are activated (Hampshire et al., 2019). According to a recent literature review (Kang et al., 2022) during the different stages of learning involved in the IBL (such as acquisition of new information, retrieval of those stored in the long term memory and implementation/integration of new instructions with the previous one) different brain regions are simultaneously activated. In particular, one of the most implicated area is the Lateral Prefrontal Cortex (Kang et al., 2022) which is related to many domain general cognitive processes that go under the name of executive functions (Moriguchi & Hiraki, 2013; P. Yuan & Raz, 2014). The term "executive functions" includes several high-level domain general cognitive processes that regulates

[1]Inquiry Based Learning (IBL): posits that the acquisition of scientific knowledge occurs through and depends on students' active engagement in problem-solving situations. This methodology consists in presenting the students with real-life conceptual problems that they need to solve. This allows them to deeply understand and to directly experience a practical application of a theoretical concept in the real-life. The application of the IBL approach relies on the subdivision of a complex scientific process into small and interconnected units. Students take part in this discovery process that guides them and encourages them to centre their attention on important aspects of scientific thinking (Pedaste et al., 2015). The strength of the IBL approach lies in its flexibility and adaptability, making it a valuable tool for teaching and learning. Furthermore, as the authors (Pedaste et al., 2015) suggest, its phases do not have a hierarchical order. This makes the use of this methodology even more complex and articulated, as it does not require the systematic adoption of a method. Finally, the crucial aspect is that it allows learning through direct students' involvement, supporting their understanding as well as the transition from theory and the real world.

thoughts and behaviours during the execution of an activity aimed at achieving a specific goal, helping people in: maintaining attention and focus, executing problem solving tasks, making thoughtful decisions (Diamond, 2013, 2020; Zelazo et al., 2016). These cognitive processes, along with other domain general processes like visuospatial skills, have been reported as significatively related to chemistry performance (Hodgkiss et al., 2018; Overton & Potter, 2011; Rhodes et al., 2016). Given the complexity of chemistry and the additional cognitive load derived from the implementation of IBL practice, it is crucial to integrate chemistry education with cognitive psychology to gain a deeper understanding of cognitive processes engaged during chemistry learning. Furthermore, this interdisciplinary approach can provide valuable tools and strategies that can be implemented to promote students' understanding and learning.

This integrated perspective has been already introduced in chemistry with the numerous studies carried out by Johnstone (1982, 1991; 1986). Following this lead, literature has been well established that executive functions (Hussein & Reid, 2009; Johnstone, 1991, 2010; Overton & Potter, 2011; Reid, 2021; Rhodes et al., 2016) as well as visuospatial skills (Harle & Towns, 2011; Hodgkiss et al., 2018; Wu & Shah, 2004) are crucial in promoting chemistry understanding and learning; however, there are no meta-analytic studies in literature that explore whether the different cognitive processes are related to chemistry learning. The complexity of the subject along with the numerous different aspects that concern chemistry (see for example Allman, 1975) make the challenge quite difficult. Finally, focussing on the Italian educational context we do not have many studies that investigates the relationship between cognitive processes and chemistry learning, especially among undergraduates' students. We do not have an updated representation of the problems that students encounter in learning chemistry; hence, the implementation of proper and effective teaching strategies is difficult. Overall, the necessity to further explore in this direction using an approach that combines chemistry education and psychology knowledge emerges, to better understand which tools can be introduced and implemented to promote chemistry learning among students, especially those that are struggling in dealing with this kind of elements and aspects.

Summing up, the present chapter aims to give an overview about theoretical knowledge about chemistry education. Furthermore, it seeks to summarize the current literature about cognitive processes involved in chemistry learning. The main cognitive processes that literature has demonstrated to be related to chemistry learning will be defined and described, and a summarization of the main literature findings about the relationship between cognitive processes and chemistry learning will be reported. The last section of this chapter will focus on the benefits given by the introduction of visualization tools. Overall, this chapter aims at providing an overview of the existing literature, in order to give a proper and solid rationale that guided us in designing and in defining our research project.

1.2 Chemistry education: struggle in dealing with chemical phenomena

Chemistry is a complex discipline that usually is introduced in middle schools or at the beginning of secondary school as part of science curriculum (it varies from one country to another). In some countries, this subject can be taught only by trained chemists (with at least a degree in chemistry), whereas in others, anyone with a general science degree may do so. In the Italian context, for example, the latter is the case. As a result, it can happen that chemistry education and chemistry learning is reduced to mere memorization of facts, laws and concepts without a deep-level understanding of how these aspects can explain phenomena directly observable in everyday life (Reid, 2021). Chemistry, indeed, likewise other sciences (such as physics and biology), enable us to grasp a better comprehension of the world.

Teaching and learning chemistry can be challenging for both students and educators, as it has been demonstrated by Johnstone (1971, 1991). One problem in chemistry education as Johnstone (1982) highlighted is that teachers/educators frequently use familiar and non-scientific words to explain complex chemistry phenomena that happen into the sub-microscopical level (atomical and molecular level) that is not directly observable. This practice of oversimplification can complicate further learning processes and can lead to misconceptions (Johnstone, 1982; Reid, 2021).

Johnstone's research (1971) revealed that students struggled primarily in chemistry topics with high information load, such as redox, thermodynamics, moles, organic chemistry, and calculation. He observed that students struggle more when they have to deal with concepts that ask to process numerous ideas, information, and knowledge at the same time. This request in chemistry is frequent (see Johnstone, 1982) since when chemists deal with a phenomena they look at it from a macroscopic point of view observing properties and behaviour. They summarize it using a symbolic language and then they move into the sub-microscopic level (using sub-atomic particles, atoms and molecules) to explain the reason behind the directly observable phenomena. The lack of fluidity in moving between these three levels of representation is one of the biggest weaknesses among students who are not chemistry experts (Johnstone, 1982). The limited brain capacity to handle and process a certain number of ideas at the same time along with the scarce knowledge in chemistry challenges novice students. Expert chemists instead can easily implement strategies organizing multiple elements into a meaningful unit (see for example, Adhikary et al., 2015; Stieff et al., 2020) reducing the overall number of ideas processed simultaneously. All this has been illustrated and summarized by Johnstone (1991) in what is today famous as "Johnstone's triangle" (see Figure 1.1)

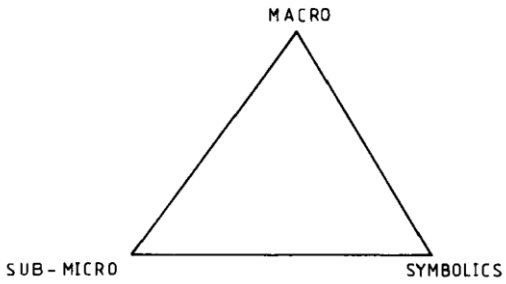


Figure 1.1 Johnstone's triangle (Johnstone 1991, p.78)

The author argues that chemistry learning, asking students to deal with not tangible concepts (such as electrons, bond energy, photons, structures and molecules), cannot be learned through direct perception. Therefore, according to him, teachers have to guide novice students in understanding the different concepts simultaneously integrating these three levels of reality: macroscopic, sub-microscopic and symbolic. They can be shortly described as it follows:

- Macro level: represents what can be directly observed or perceived throughout senses (sight, smell, touch, hearing and taste).
- Sub-micro level: concerns what happens at the particle level (like atoms and molecules) and cannot be directly observed.
- Symbolic level: consist of all the symbols, formulas, and equations that are used in chemical language to describe a chemical phenomenon.

Defining this model Johnstone (1991) underlines the complexity of dealing with all levels at the same time, especially for non-expert students since it overwhelms their brains resources, leading them to confusion, and it might arise misconceptions. This idea of cognitive load has been integrated with cognitive studies about human brain capacity to handle and process information (Baddeley, 2000; Baddeley & Hitch, 1974; Miller, 1956). In other words, what Johnstone (1971, 1982, 1982, 1991, 2010) concluded in his works is that chemistry requires careful and step-by-step teaching, in order to not overload the students' brains resources. In particular, he empathized the role of a specific domain-general cognitive process: working memory. Additionally, students struggle more when they have to deal with the sub-sub-microscopic level (Chittleborough, 2014; Johnstone, 1991) as their cognitive resources are limited and they have to handle multiple mental representation, integrating them with the other two level of reality.

1.2.1 Human brain capacity to handle and process information

As already mentioned in the previous section, chemistry is hard because learning this topic asks people to deal with complex ideas across multiple levels, and their brains are not designed to process and handle all of that simultaneously, especially during the learning experience

(Johnstone, 1982, 1991). The author, integrating chemistry education with cognitive psychology, was able to explain the struggles of students in dealing with this discipline.

In this regard, one of the first authors to investigate the limited human capacity to hold information in mind was Miller (1956). He introduced the concept of short-term memory, observing that among adults the average number of ideas that can be processed simultaneously is seven (ranging from five up to nine, according to individual differences). In other words, people have a limited capacity of handling a certain number of ideas at the same time. There are some individual differences, but when the number of information overcomes this limited-space we need to find strategies to reduce this number. Miller (1956) introduced the concept of a "chunk", defined as a single unit of information. Multiple meaningless information (such for example single letters "A", "T", "O", "M", "S") can be summarized in a whole unit (as a single word for example "ATOMS"). This strategy, known as chunking, reduces the individual overload, and it has been observed to be useful in chemistry learning too (Adhikary et al., 2015; Stieff et al., 2020). However, the concept of short-term memory is too reductive, and it does not consider that during learning information is not simply held but manipulated and updated. Consequently, a few years later, the concept of working memory (WM) was introduced (Baddeley, 2000; Baddeley & Hitch, 1974), and it can be imagined as the mental board where information is dynamically handled, manipulated and integrated with previous information stored in the long-term memory

WM is a domain-general cognitive process that is hugely involved in learning activities as it manages the manipulation of the information as well as the simultaneous integration between new and previous knowledge. However, the WM has the same limited-capacity that Miller (1956) reported when describing the short-term memory. Therefore, WM of experienced chemists functions more efficiently, as they can readily "chunk" the numerous information in a meaningful unit (Reid, 2021). In this regard, significant are the studies implemented by Johnston and El-Banna (1986, 1989) that widely explored the relationship between WM abilities and students' ability to solve a chemical task/problem. The authors assessed the students with different chemistry tasks with an increasing level of burden on WM resources. The high demanding tasks were chemistry problems that entail multiple steps and to handle much information simultaneously. They tested more than 20 000 high school students (average age of 16 years old), who performed exactly as predicted: students succeeded easily on beginner-level tasks that placed low demands on WM, but their performance declined sharply once the task load exceeded approximately six units of information. Meaning that only a small number of students with better WM ability (or more expert in chemistry) were able to deal successfully with more demanding problems. Additionally, they assessed students' WM ability using the digit span task[2], and their visuo-spatial skills with Figure Intersection Test[3]. In accordance with Miller (1956), they observed that students' capacity varied from 5 to 9, and that the average score was 7. What they observed was that students' with higher WM capacity

[2] The task asks the student to listen to a series of single digit, presented in a random way, and to recall them in the correct order of presentation.

[3] The task assesses the individual ability to identify partially hidden and overlapped geometrical figures.

could perform successfully in tasks that have a load of more than 6; vice versa those with lower WM performance could struggle in dealing with low demanding tasks (Johnstone & El-Banna, 1986, 1989).

Overall, it emerges that WM, but more precisely the individual brain ability to handle and process information, can sensibly affect chemistry learning performance. This first conclusion, that has been well established in literature, gave us a better understanding of the reason behind the challenge of dealing with multiple information simultaneously. However, it does not take into consideration the peculiarity of chemistry: it is a highly demanding subject since it requires to manage and to interconnect three different levels of reality. This is particularly true in higher levels of education in which students are asked to cope with the submicroscopic level even more, and teachers usually give for granted their ability to interconnect this level with the macroscopic and the symbolic one (Chittleborough, 2014; Johnstone, 1991).

1.2.2 Understanding the sub-microscopic level

Johnstone (1971, 1982, 1982, 1991, 2010) summarized the complexity of chemistry learning as the combination between limited working memory resources and the necessity to interconnect constantly three levels of reality. In particular, the author pointed out that a crucial challenge can arise when students have to deal with the microscopic level, as they need to handle and process abstract concepts such as atoms, molecules, electrons, ions, etc (Chittleborough, 2014; Chittleborough & Treagust, 2007; Nicoll, 2003). The explanation of this knowledge usually relies on iconic images (pictures or animation) that help the students to visualize what cannot be directly observable. Despite these representations are an oversimplification of the reality and might sometime develop misconceptions (Arini et al., 2025; Eilks et al., 2012; Slapničar et al., 2017), they can be crucial in promoting students' understanding and are hugely implemented (Stieff & Ryan, 2013). For example, the comprehension of the phenomena that happen at the particulate level is hugely supported by sub-micro representations and their use seems to guarantee a better learning (Bunce & Gabel, 2002; Devetak & Glažar, 2010; Pavlin et al., 2019; Wissiak-Grm & Devetak, 2022). These representations can be static or animated models that foster the understanding and the explanation of the particles' interactions. In their literature review, Wu and Shah (2004) concluded that it is fundamental to support students' visuospatial thinking and their ability to promote their learning. The authors highlight the importance of giving the students multiple and different type of representations (static, dynamic, and both 2D and 3D models); this might provide a more inclusive approach. Similar to other domain general cognitive ability, the visuospatial one can vary among individuals, that is why implementing different representations allows the teacher to give different kinds of support according to their different profiles. For the same reason the authors also suggest that it might be useful to: explain the dynamic interactions that happen at sub-microscopic level; sustain and illustrate how to move from 2D to 3D representations; explicate the conceptual aspects reported in the visual representations (Wu & Shah, 2004). Applying these tips enable the teacher to scaffold students

throughout their learning and understanding process, as well as reduce the cognitive load that they might experience if they had to handle all on their own. Finally, this approach could be particularly advantageous for those students with weaker domain-general resources (working memory and visuospatial skills), that usually are more challenged in chemistry learning (Hussein & Reid, 2009; Wu & Shah, 2004).

1.3 Domain-general cognitive processes involved in learning

In this paragraph, we will present and define the main domain general cognitive processes that are involved in chemistry learning and understanding. The processes discussed in this section are not specifically related to chemistry, but they represent a valuable resource in promoting academic achievement in this discipline.

1.3.1 Executive Functions (EFs)

Executive functions are defined as goal-oriented cognitive processes that control and monitor human behaviour, promoting the achievement of chosen aims (S. W. Anderson, 2008; Diamond, 2013; Miyake et al., 2000). In other words, they are a set of cognitive processes that play a crucial role in many learning and daily activities: some skills manipulate and handle the needed information, while other inhibit the excessive ones that may unnecessary overload cognitive recourses; other skills are entailed in the planification of steps required to fulfil the task; other processes are engaged in the regulation of the attentional resources (Marzocchi & Valagussa, 2011). Given their huge involvement in many different fields, they have been massively investigated in literature, and there are different models and research that tried to provide an overall definition of these skills (Baggetta & Alexander, 2016; Dias et al., 2024). According to a recent systematic review focused on educational field (Baggetta & Alexander, 2016), EFs are a multidimensional construct and numerous are the skills that can be categorized and included in the various models that have been theorized in literature. Overall, it is collectively accepted that there are three core EFs: the working memory (WM); the inhibitory control; and the cognitive flexibility (Diamond, 2020).

Initially, executive function has been conceptualized as a whole construct (Baddeley & Hitch, 1974; Norman & Shallice, 1986). During the 1990s numerous factorial studies pointed out consistent findings that were summarized in the model proposed by Diamond (2013, 2020). The first two models that provided a multicomponent definition EFs domain are Levin et al. (1991) and Welsh et al. (1991). The two groups proposed two separated models that are partially overlapping: they both identified the factor named “Planification” and they both recognized the presence of a factor that can be related to cognitive flexibility – “Concept formation” for Levin et al. (1991) and “Fluid & Speeded Response” Welsh et al. (1991). Later, Lezak (1995) proposed another model, oriented to clinical setting and assessment. The author identified four main executive domain: “volition” that underlie the conscious decision making; “planning” all the steps allowing goal-achievement and problem-solving; “intention to act” that sustains the

accurate execution of actions and flexible adapts the action to the co-occurrent circumstances; "action" that concerns monitoring the proper execution of each step and the simultaneous updating according to internal and external feedbacks. The major limitation of this model is that it does not mention some crucial processes such as working memory and the inhibitory control. This problem was overcome with the model of Roberts and Pennington (1996) suggesting that human behaviour can be better understood as the dynamic interaction between working memory resources and inhibitory control systems. The first one can be defined as a dynamic limited-capacity system that temporarily stores, manipulates and transforms verbal and visual information (Baddeley & Hitch, 1974; Pennington, 1994). The inhibition, instead, has a role in suppressing automatic responses or to interrupt a specific action that may interfere with the implementation of a higher-priority task. Hence, these two processes are independent, but they work in interaction with each other.

In the same year, Pennington and Ozonoff (1996) in their literature review focused on the executive functions (EFs) as the cognitive skills that allow people to carry out a goal-directed action. The authors defined EFs as separated from memory and language, but as partially overlapped to attention, reasoning, and problem-solving. Their work brought a significant contribution explaining the relationship between EFs and developmental disorders. Similarly, Barkley (1997, see also 2000, 2011) stressing the attention on people with atypical development profiles, focused particularly on students diagnosed with Attention Deficit Hyperactivity Disorder (ADHD), and prosed a multicomponent model of EFs. The author gave a central role to self-regulation and identified four crucial executive neuropsychological functions: working memory; self-regulation of affect-motivation- arousal; internalized/self-directed speech; and reconstitution (involving analysis and synthesis of events). The model (see Figure 1.2) recognizes the EFs as crucial in predicting and regulating human behaviour.

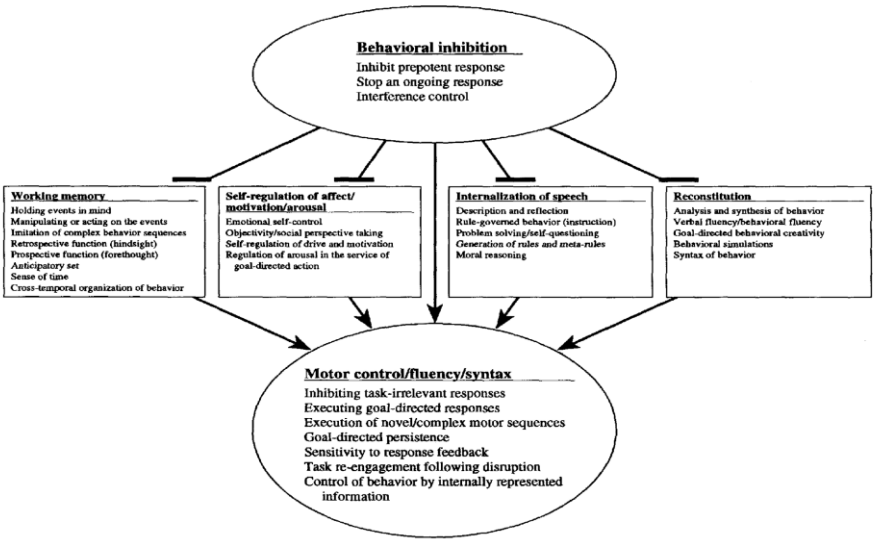


Figure 1.2 Schematic representation of Barkley model (Berkley 1997, p. 73)

The multicomponent structure of the EFs has been confirmed also with the systematic review implemented by Miyake at al. (2000). The authors chose to focus the attention on cognitive flexibility (shifting), working memory and inhibition. Once again, findings confirmed that EFs can be described as a set of different cognitive processes/skills that operate independently, while functioning in dynamic interaction.

Partially different is the model proposed by Anderson (2002), as in this model the executive function is conceptualized as a whole control system that entail four different domains (see Figure 1.3) in accordance with the view proposed by Alexander and Stuss (2000).

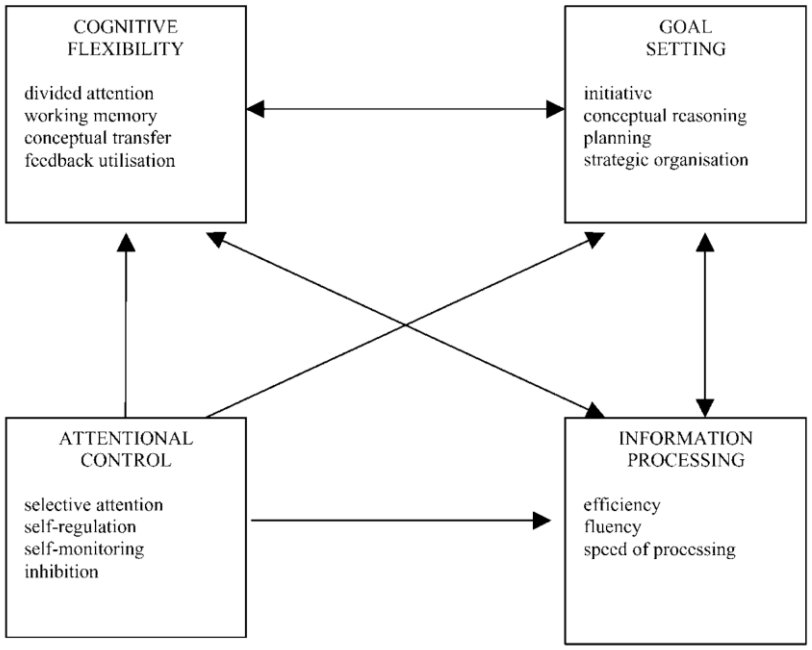


Figure 1.3 Schematic representation of Anderson's model (Anderson 2002, p. 73)

The weakness of these models is that they are insufficient in describing the complexity of human behaviour. Therefore, Zelazo et al. (1997) and Burgess et al. (2000) suggested two different sequential models that represent a more ecologic description of goal-directed actions. The first ones conceptualized the EFs as a series of different processes that operate in an integrated manner focussing the attention of the metacognitive and strategic aspects. According to the model, it is possible to explain EFs within the problem-solving framework; therefore, they identify four distinct phases: representation, planning execution and evaluation. Overall, the model does not define the EFs but it illustrates the processes that are involved in the executive domain. Burgess et al (2000), instead, studying patients with frontal lesions clarified, theorized and tested with a structural equation model that describe the needed steps to execute a task: learning and remembering the task' rules; planning the actions; execute the task; evaluate

the coherence between the plan and the execution; recall the quality of execution and implement the possible improvement.

In summary, the EFs can be identified as a set of distinct dynamic processes that are activated during the execution of a goal-directed behaviour. Therefore, they are hugely related to learning success (Bahri Roudposhti & Al Abdwani, 2024).

1.3.2 Working Memory

The concept of working memory (WM) was introduced by Baddeley (Baddeley, 2000; Baddeley & Hitch, 1974), and it can be imagined as the mental board where information is dynamically handled, manipulated and integrated with previous information stored in the long-term memory. As we have observed in the previous section, according to some models (Barkley, 1997; Diamond, 2013; Pennington & Ozonoff, 1996; Roberts & Pennington, 1996) it can be considered as a core process included in the EFs. However, all these models recognized WM as an independent system/process that functioned in an integrated manner with other EFs.

One of the most famous model defining the WM is the one originally proposed by Baddeley and Hitch (1974), that was revised at the beginning of the XXI century (Baddeley, 2000) see Figure 1.4.

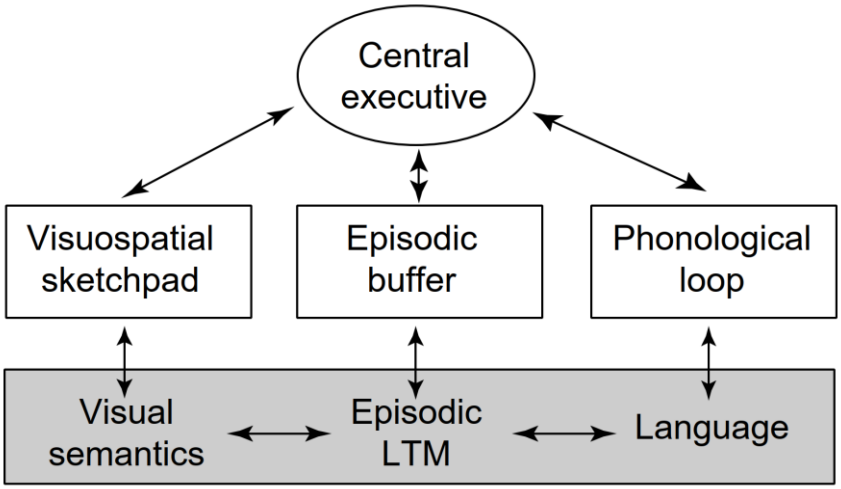


Figure 1.4 Working memory organisation (Baddeley, 2000, p. 421)

The model originally described the WM as a dynamic process consisting of two domain-specific processes, the visuospatial sketchpad and the phonological loop, designated to handle and manipulate visuospatial and verbal information respectively. The more recent version (Baddeley, 2000) introduced a third crucial component: the episodic buffer. This additional component was described as a limited-capacity system that transitory maintains and integrates the information from multiple sources. Additionally, it plays a pivotal role interconnecting the

new knowledge with those stored into Long Term Memory. Finally, all these components are coordinated by the central executive, a limited-capacity attentional control system which mediates the flow of information (Baddeley, 1996, 2000). A detailed illustration of the most recent version of this multicomponent model of WM has been summarised in Baddeley et al. (2020) and reported by Hitch et al. (2025), see Figure 1.5.

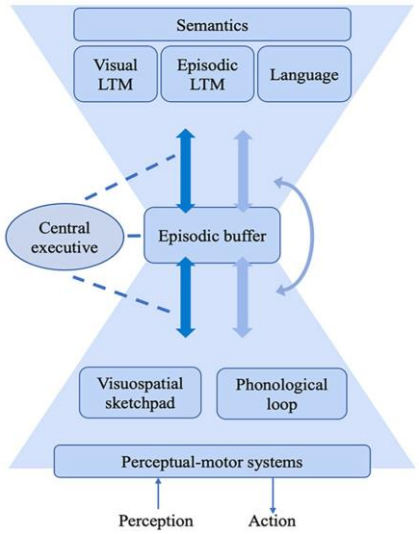


Figure 1.5 Multicomponent model of WM Hitch et al. (2025, p. 228)

The newest version of the model (Figure 1.5) includes the same components reported in Figure 1.5, but it gives the episodic buffer a central hub role. Additionally, the central executive is defined as a separate control resource system interacting with the different components in multiple manner (Hitch et al., 2025).

Along with the traditional model (Baddeley, 1996, 2000; Baddeley et al., 1984, 2020; Baddeley & Hitch, 1974; Hitch et al., 2025; Larsen & Baddeley, 2003), since late 1990s a parallel path of investigation focussed on visual components of WM emerged (Oberauer & Lin, 2024). The studies oriented in this direction confirmed that visual WM is a limited-capacity process where a certain number of visual objects can be held (Cornoldi & Vecchi, 2003; Fukuda et al., 2010; Luck & Vogel, 1997; Richardson & Vecchi, 2002; Rouder et al., 2008; W. Zhang & Luck, 2008). A few years ago, Oberauer and Lin (2017) attempted to integrate traditional literature about WM and the one about visual WM. They proposed the Inference Model suggesting that visual WM components encoded the item in relationship to their spatial location and employed the spatial location as a cue in the retrieving phase. Both components of WM (verbal and visual) when handling or manipulating elements – such as words/nonwords or visual objects - encode these items according to their serial position into a list or to their spatial location (Oberauer & Lin, 2017, 2024). The authors concluded that the two domain-specific WM components partially rely on common processes and work in a comparable way, but they process two different types of material. The recent models (Hitch et al., 2025; Oberauer & Lin, 2017, 2024) have clearly illustrated that WM is a dynamic cognitive process that deals with the

retention and the manipulation of verbal and visual material. Its resources are limited, but its efficiency can be improved by strategies (Adhikary et al., 2015; Miller, 1956; Nassar et al., 2018; Stieff et al., 2020).

In summary, WM has a pivotal role in promoting learning achievements and academic success throughout the development (Hitch et al., 2025). Students are constantly exposed to textual and visual material, and as reported by Cowan (2014) there is a wide literature providing solid evidence that good WM capacity is associated with better performance in concept formulation and with more efficient control processes.

1.3.3 Fluid Intelligence

The term "Fluid Intelligence" in literature has been employed interchangeably with words like: "nonverbal intelligence", "reasoning ability", "intelligence" (K. Yuan et al., 2006). It can be identified as the ability to intentionally recognize rules and patterns, allowing to solve novel tasks that cannot be resolved with automatic procedures. This is possible thanks to the support of multiple cognitive processes such as: General Sequential (deductive) Reasoning, generating conclusions from a pull of given starting conditions, following a hypothetico-deductive reasoning; Induction, discovering underlying rule or pattern from a set of observations and applying them to new situations, combining information into generalizations, inferences, or hypotheses; Quantitative Reasoning, dealing inductively and/or deductively with mathematical concepts, and properties; Piagetian Reasoning, acquiring and applying logical thinking skills such as seriation (ordering elements logically), conservation (understanding that quantity remains constant despite changes in appearance), and classification (grouping items based on shared properties); Speed of Reasoning, quickly and fluidly generating possible rules or solutions within a limited time frame (McGrew, 2009; McGrew & Evans, 2004). This concept was introduced by Cattel and Horn (1966) and later integrated with the contribution of Carrol (1993). The model is known as CHC (Cattel-Horn-Carrol) and it has gained a high popularity in literature (McGrew, 2005, 2009). However, it is necessary to highlight the fundamental steps that were pivotal in structuring this model.

Galton (1883) was the first to show an interest in the quantitative measurement of human mental abilities. The author theorized the existence of a general metal ability underlying all cognitive abilities, that was actually measured few years later (J. McK. Cattell & Galton, 1890). These assumptions were later integrated and expanded by Spearman (1904, 1927), who identified that there is a common function/group of functions that is shared among all different intellectual abilities. He defined "General Intelligence" (G factor) as one function/group of functions and "S factors" the numerous intelligence skills. In other words, he identified in the "G factor" the core of all mental activities. Throughout the XX century numerous authors attempted to develop instruments and scales that measure human intelligence. At the beginning of the century Binet and Simon (1904) developed a test that quantitatively assessed people' mental ability; and few years later Wechsler (1939) designed a scale to measure adults' intelligence. Few years later, Thurstone (1936) computed a factor analysis and the results

pointed out an alternative structure of intelligence, confuting the "G factor" model proposed by Spearman (1904). The findings reported by the author suggested that human intelligence relies on seven independent abilities: visual imagery, perceptual speed, memory, word fluency, number facility, inductive reasoning, and verbal comprehension. The author expanded the previous literature, overcoming the single-factor structure of intelligence that was originally proposed. Finally, the CHC model (J. B. Carroll, 1993; R. B. Cattell & Horn, 1966), defined few years later, provided a new interpretation that integrated the unitary model promoted by Spearman (1904) and the multiple one supported by Thurstone (1936).

The CHC model assumes that it is possible to identify multiple and partially independent primary mental skills; furthermore, it claims that it is possible to distinguish a whole unique "g" factor explaining part of the variance of the single mental abilities (R. B. Cattell & Horn, 1966). The authors distinguished between Fluid and Crystallized Intelligence, the first is the ability to reason and solve a task independently from prior knowledge. The Crystallized one, instead, has been defined as the ability needed to execute a task relying on individual mastery to store and recall knowledge from long term memory, in other words it is a store of verbal and procedural knowledge. The latter, is the result of a learning process, and its development can be influenced by personality and cultural factors (R. B. Cattell, 1971). The two components (Fluid and Crystallized factor) have been described as separated, but as Cattell (1943, 1963, 1971) had originally postulated, the Fluid intelligence shore up the development of the Crystallized one, since the first is highly involved in the acquisition of new skills, competences, and knowledge. The contribution of Carroll (1993) clarified how the two components are not completely independent since they are second order factors, and the author hypothesized that a third-order factor correlating with Fluid intelligence (J. B. Carroll, 1993; Gustafsson & Åberg-Bengtsson, 2010).

In summary, the fluid intelligence can be defined as a nonverbal and cross-cultural skill that allow people to deal with novel tasks/problem, not requiring prior knowledge to solve it. Hence, it has been demonstrated that this cognitive skill is highly related to learning and academic success (Lozano-Blasco et al., 2022; Primi et al., 2010; Romero et al., 2024; K. Yuan et al., 2006).

1.3.4 Visuospatial skills

The term "visuospatial skills" refers to a set of mental processes allowing the person to encode, maintain, process and manipulate visual and spatial information such as mental rotation of objects, identification of simple shape within complex figures (Linn & Petersen, 1985; Trojano et al., 2018). These skills are crucial in various everyday life activities such as drawing, designing a model, or building a Lego/furniture following the pictorial instructions (Mervis et al., 1999). In other words, all the tasks required to deal with symbolic and non-verbal information are loaded on visuospatial skills (Linn & Petersen, 1985). De Renzi (1982), in describing visuospatial skills, distinguished between "spatial perception" and "spatial thought". The first is the primary ability to process visual material without the need of other cognitive

processes such as memory, mental rotation, verbal mediation or further intellectual analysis. On the other hand, the "spatial thought" entails the implementation of cognitive processes such as spatial integration or mental rotation. However, in literature other alternative categorizations are proposed like the one by Linn and Petersen (1985) and recently confirmed by Mitolo et al (2015). The authors, focusing the attention on the cognitive processes that individuals have to activate to solve the different visuospatial task, identified three categories: "spatial perception", "mental rotation" and "spatial visualization". The first concerns the ability to determine spatial relationships between objects and individual body position. The mental rotation, instead, is the ability to quickly and accurately imagine the rotation of 2D or 3D figures/objects. Finally, spatial visualization refers to complex visuospatial tasks that need challenging and multiple steps, requiring the person to integrate and manipulate many visuospatial information.

Linn and Petersen (1985) categorization was later integrated in a more complex discriminative model proposed by Uttal et al.(2013). The authors conducted a meta-analysis to explore the effect-size of visuospatial training and whether this effect persists through time and whether the positive effect can be transferred to new tasks. The discrimination proposed by Uttal et al.(2013) identifies four aspects that are given by the intersection of two dimensions: Intrinsic vs. Extrinsic; Static vs. Dynamic (see Figure 1.6). The first distinguishes between dealing with how the different parts within an object are related (intrinsic) and comprehending the relationships between different objects (extrinsic). Therefore, the first group is frequently related to the small-scale domain and the second one to the large-scale domain according to Hegarty et al. (2006) discrimination. Furthermore, the second dimension (static vs. dynamic) differentiates between fixed stimuli or moving/moved objects.

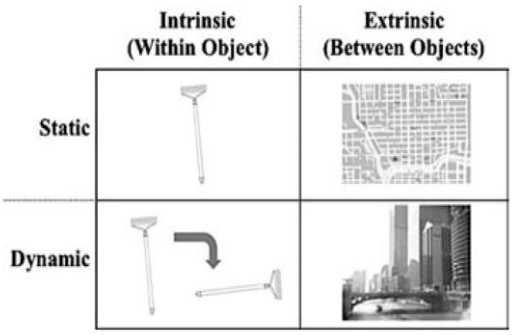


Figure 1.6 Uttal et al. (2013, p. 354) classification of visuospatial skills, and a pictorial example to discriminate the differences between the four processes.

The Intrinsic-Static process consists in identifying objects, paths or spatial configuration as well as ignoring the distractors; hence, it corresponds to the spatial visualization into Linn and Petersen (1985) classification. The Intrinsic-Dynamic, on the other hand, supports more complex tasks that require the integration of multiple items into a more complex configuration or to mentally represent, transform (from 2D to 3D or vice-versa) or rotate visual elements; this second process partially overlaps with both spatial visualization and mental rotation into Linn and Petersen (1985) classification. The Extrinsic-Static process is related to the ability to

understand some basic spatial concepts such as the invariance of spatial relationships between objects, corresponding to the spatial perception in the previous classification proposed by Linn and Petersen (1985). Finally, the last process Extrinsic-Dynamic is the innovative one and it can be described as the ability to mentally visualize a room/environment from a different point of view without moving into it.

This brief literature overview provides solid evidence about the complexity of cognitive processes involved when we refer to "visuospatial skills". Overall, the different aspects are partially independent, but as reported by Hegarty et al. (2006), among adults the performance in small-scale and large-scale visuospatial tasks partially converge, suggesting that at least part of the cognitive processes involved to solve them are shared. It is possible to conclude that the visuospatial domain is a set of different abilities/processes allowing to handle, manipulate and solve problems concerning symbols and nonverbal information (Linn & Petersen, 1985; Mitolo et al., 2015; Uttal et al., 2013). Since visuospatial is a cognitive domain, it means that its distribution among the population can vary from one person to another; people, indeed, possess different degrees of visuospatial ability (Mervis et al., 1999). The visuospatial skill can provide a solid support to learning, especially in those subjects that challenge students with multiple verbal and visual information, like for example science topic (Uttal et al., 2013).

1.4 Cognitive processes and science learning: the case of chemistry learning

In literature there are several studies investigating the relationship between cognitive processes and science learning (Berkowitz & Stern, 2018; Bull et al., 1999; Bull & Scerif, 2001; Gathercole et al., 2004; Giofrè et al., 2018; Hinze et al., 2013; Jarvis & Gathercole, 2003; Kyttälä, 2008; Kyttälä et al., 2003; Latzman et al., 2010; St Clair-Thompson & Gathercole, 2006; Stieff et al., 2020; Uttal & Cohen, 2012). These disciplines are frequently implementing an investigative approach, typical of the Inquiry-Based Learning (see section 1.1 of the present chapter). Therefore, students are presented with a concrete problem, and they are required to reason to find the solution, and throughout this process they understand the generalized law that explains the studied phenomena (Pedaste et al., 2015). To achieve this goal, students have to be endowed with good reading skills, allowing them to understand written text presented in the initial phase (Orientation) and in the phase of in-depth study of the literature (during the Conceptualization). Additionally, the success in the inquiry activities relies on other domain-general cognitive processes such as problem-solving skills[4]. Furthermore, students are required to collect, record and maintain, but also select and interpret the data in light of the literature (Investigation phase, in particular the Data interpretation sub-phase). This can be managed, processed and coordinated thanks to the activation of the working memory (Al-Ahmadi &

[4] Problem-solving can be described as the cognitive processes (such as reasoning, or creative thinking) activated when the person is challenged to overcome an obstacle, to implement a plan allowing them to reach the desired goal or to draw conclusions (American Psychological Association, n.d.)

Oraif, 2009). This dynamic system shores up students in maintaining, handling, manipulating, and integrating verbal and visuospatial information (see section 1.3.2 of the present chapter).

Multiple investigations have been developed in order to identify the cognitive processes relevant in supporting science learning and problem-solving ability, pointing out the pivotal role of working memory (St Clair-Thompson & Botton, 2009). Literature (e.g., Bull & Scerif, 2001; Gathercole et al., 2004; Hodgkiss et al., 2018; Latzman et al., 2010; St Clair-Thompson & Gathercole, 2006; Stieff et al., 2020; Uttal & Cohen, 2012; K. Yuan et al., 2006) includes multiple evidences concluding that learning in science education relies on the acquisition of both domain-specific skills (e.g., calculation, knowledge of particular procedures, technical/discipline-related vocabulary) and domain-general skills such as working memory, attention, and inhibition. For example, Bull and Scerif (2001) explored the relationship between maths performance and executive functions, and observed that children with lower mathematical skills achieved low scores in inhibition and in the working memory tasks. The authors, computing a regression analysis, found that inhibition capacity and working memory contribute to explain a significant amount of variance in mathematics skills, the 6% and the 10% respectively. A consistent result was reported by Gathercole at al. (2004), the authors investigated a sample of students of primary (3rd grade) and secondary school (10th grade) and observed that in both groups their math achievements were significatively related to their performance in the working memory tasks. In the older group (10th grader) the authors also collected students' science level observing that working memory performance is significatively related to science achievement too. Similar results were observed by St Clair-Thompson & Gathercole (2006) focusing on secondary school students (11-12 years old). They explored how working memory (verbal and visual components) and executive functions (more precisely: shifting, updating, inhibition) tasks are related to academic achievement. The finding showed that inhibition ability was associated with science and maths levels, additionally they highlight that maths and science achievement were significatively related to visual working memory tasks but not to verbal ones. These results were consistent with Latzman et al. (2010) finding a significant relationship with the inhibition and with K. Yuan et al. (2006) highlighting a significant relationship between science learning and working memory. Finally, more recently an investigation on children (age range 7-11 years old) confirmed that students performance in visuospatial tasks such as mental folding or spatial scaling, was positively related with the science scores, more precisely the visuospatial skills explained the 8% of variance in the science scores (Hodgkiss et al., 2018). Among all these cognitive processes, the most studied are certainly working memory and the visuospatial skills.

There are various studies in literature (Bull & Scerif, 2001; Danili & Reid, 2004; Gathercole et al., 2004; Gómez-Chacón et al., 2014; Hussein & Reid, 2009; Kyttälä, 2008; Rhodes et al., 2016) that have investigated how working memory components (verbal and visuospatial ones) are related to the science academic success. The different studies confirmed that working memory positively correlates with both learning and achievement in scientific tests. Working memory, in this context, can be pictured as the mental space within which multiple verbal and visual information is maintained, handled, manipulated and processed simultaneously in order to complete the task/problem (Gathercole et al., 2004; Gathercole & Pickering, 2001). Some authors (Carter et al., 1987; Kyttälä, 2008; Kyttälä & Lehto, 2008; Rhodes et al., 2016; Stieff

et al., 2020; Uttal & Cohen, 2012) have focused on visuospatial components of working memory, highlighting the crucial role of this process in promoting learning and success in scientific disciplines. The explanation and the comprehension of scientific concepts rely on both verbal and visual (pictures or graphs) information, and for this reason a good working memory as well as an efficient visuospatial working memory might play a pivotal role. The present assumption is supported by Rhodes et al. (2016) findings. The authors investigated whether visuospatial working memory and other executive functions (inhibition, attention and planning) are able to predict the students' performance in a chemistry learning task. Their regression analysis confirmed that, among all these domain-general cognitive processes, the only significant predictor of the chemistry performance was the visuospatial working memory. Analogous results were reported by Kyttälä & Lehto (2008) who have investigated the relationship between students' performance in a mathematics and in a geometry task and their scores in the visuospatial working memory tasks. The authors assessed 135 secondary school students (15-16 years old) with a non-verbal fluid intelligence task and with three different visuospatial working memory tests: the sequential maintenance task [5] (passive); the simultaneous maintenance[6] task (passive); the mental rotation task (active)[7]. The passive tasks require only maintenance or retrieval of information, while active ones involve maintenance as well as processing and manipulation of information (the authors' approach is consistent with Cornoldi & Vecchi, 2003). They observed that the non-verbal fluid intelligence test was related to maths performance (arithmetic and geometry), and they observed that both passive and active visuospatial working memory components were positively related to maths ability. Focussing on the separated domains the results highlight that passive aspects are more related to calculation, whereas the active aspects are more related to geometry.

Visuospatial skills are crucial in all scientific disciplines, since students are frequently presented with 2D or 3D representations alongside theoretical explanation. These skills have been defined, in science education literature (see for example, Uttal & Cohen, 2012), as cognitive processes needed in the formulation, the encoding and the mental manipulation of 3D objects. There are evidences in literature (Wai et al., 2009) that visuospatial skills can predict academic success in scientific disciplines. The authors implement a longitudinal study involving 400.000 students over half a century. Their findings showed that these skills can predict both the probability of pursuing a scientific degree course studies as well as the chance to have a successful career. The students were assessed with tests measuring their cognitive potential (mathematical, verbal and visuospatial competence), and their level of knowledge in multiple disciplines such as science (biology, engineering, physics), art, and journalism. Finally, the authors investigated students' aptitudes and interests towards the different subjects, and their personality. The results revealed that students that achieved high levels of education

[5] Sequential maintenance task: the experimenter touched the block following a specific order, participants were asked to recall the sequence they have seen.

[6] Simultaneous maintenance task: participants were presented with a matrix pattern (part of the squares were coloured) that after two seconds it was covered, and they were asked to recall the pattern they have seen.

[7] Mental rotation task: participants were presented with a 2D projection of a 3D abstract object (target) and other four similar alternatives representation; they need to identify among the four items the two that represent the rotated mirror abstract object (target).

or who had a successful career in the science field, obtained very high scores in visuospatial tests.

In summary, this brief literature overview compiles multiple findings that converge on a similar conclusion: academic success in scientific disciplines largely relies on domain-general skills, among which executive functions, working memory (verbal and visuospatial components) fluid intelligence and visuospatial skills emerging as key contributors. Literature highlights how the combined work of domain-specific and domain-general cognitive processes are necessary at the basis of learning in scientific disciplines, however, most of these studies involved primary and secondary school students. In high levels of education (university level) the amount of specific knowledge needed to succeed is high, and the contribution of domain-general cognitive abilities remains significant (Berkowitz & Stern, 2018; Wai et al., 2009). However, the amount of variance explained by these cognitive processes decreases as education progresses. Studies on children and young adolescents (e.g., Giofrè et al., 2018; Jarvis & Gathercole, 2003; Kyttälä et al., 2003; Rhodes et al., 2016) reported a greater role of visuospatial working memory in explaining differences in performance compared to similar studies conducted on older students (Kyttälä & Lehto, 2008). This observation is consistent with the finding observed by McKenzie et al. (2003),, exploring the relationship between verbal and visuospatial components of working memory and maths performance in 6-7 year-old children vs. 8-9 year-old children. They reported that visuospatial components of working memory are more involved early stages of learning, and they hypothesize that the major engagement can be a consequence of the inadequate development of the sub-vocal repetion skills of the verbal working memory that reaches the full development at an average age of 9 years old (Carretti et al., 2022; McKenzie et al., 2003; Palmer, 2000). Hence, this developmental explanation (the more they grow and acquire more solid domain-general competence, the more they implement complex strategies to support their learning process) together with the need to recall numerous previous knowledge can clarify why these domain-general cognitive processes are still relevant to understand science topic, but they are not sufficient to explain a large amount of variance in science performance.

1.4.1. Cognitive processes and chemistry learning

The research project presented in this context (see Chapter 3 and 4) focuses on chemistry learning. Therefore, it is relevant to the purpose of this work to examine the literature that explores the relationship between cognitive processes and chemistry learning. As widely explained in section 1.2, the constant demand to interconnect three different level of reality can overload the individual's cognitive resources (Johnstone, 1971, 1991, 2010; Reid, 2021). In literature there are some studied that attempted to measure the relationship between cognitive processes and chemistry learning/academic performance (Bodner & McMillen, 1986; Chandran et al., 1987; Hodgkiss et al., 2018; Huang & Liu, 2012; Li et al., 2020; Nedungadi & Shenoy, 2023; Niaz, 1987, 1988; Nolte et al., 2024; Overton & Potter, 2011; Pribyl & Bodner, 1987; Rau, 2018; Rhodes et al., 2016; Robinson & Niaz, 1991; Romero et al., 2024; St Clair-Thompson et al., 2012; Stamovlasis & Papageorgiou, 2012; Stull et al., 2012; Tsaparlis, 2005; Tsaparlis et al., 1998; Upahi et al., 2020; Urhahne et al., 2009; Vilia et al., 2017). Overall,

similarly to what we conclude describing the studies in science education, chemistry understanding relies on domain-specific cognitive processes such as vocabulary, computing ability, a wealth of theoretical knowledge as well as on domain-general ones (such as executive functions, working memory, visuospatial ability and fluid intelligence). Previous knowledge, especially in high level of education have a crucial role, since it has been demonstrated that exiting knowledge shape the way students represent new information in their mind (Glaser, 1991). A recent study (L. Zhang et al., 2021) demonstrated that this is true also in younger students. The authors assessed over 300 nine-graders students (mean age 14 years and 6 months) with a paper-and-pencil chemistry test that consists of 30 items including both multiple-choice and open-ended questions. The test measures students' understanding of two concepts: "matter" (item 1 to 15) and "chemical changes" (item 16 to 30). Each item was scored dichotomously, with one point awarded for a correct answer and zero for an incorrect one (total possible score = 30). Throughout a meticulous analysis of students' answers they obtained a measurement of their knowledge structure (describing how the students have organized and created relationship between concepts in their long-term memory), their cognitive perspectives (defined as the students' personal understanding and interiorization of a chemical concept), and their cognitive patterns (the students' cognitive flexibility in interconnecting the three levels of reality: micro, macro and symbolic). The authors observed that students' academic performance in chemistry was positively and significantly correlated to knowledge structure ($r = .82$, $p \leq .010$), cognitive perspectives ($r = .86$, $p \leq .010$), and cognitive patterns ($r = .74$, $p \leq .010$). Nevertheless, students' differences in learning/understanding chemistry topics are partially explained by domain-general cognitive processes as literature has demonstrated. The complexity of the discipline and the multitude of topics/branches included in chemistry education make it harder to reach a solid conclusion about the involvement of the various cognitive processes. In this section we will try to illustrate the most relevant finding reported in literature, gaining a more accurate comprehension of how executive functions, working memory, fluid intelligence and visuospatial skills are related to chemistry performance.

The first studies that integrated the chemistry education with the cognitive psychology perspective are those carried out by Johnstone (Johnstone, 1971; Johnstone & El-Banna, 1986, 1989). Following this approach, in the same period, other authors found results that support the precious value of considering the domain-general processes involved in chemistry learning. For example, Chandran et al. (1987) assessed a sample of 11-grader children with multiple cognitive tasks: the Test of Logical Thinking – TOLT (Tobin & Capie, 1981)[8]; the Hidden Figures Test - HFT (Education Testing Service, 1966)[9]; Figural Intersection Test – FIT (Burtis & Pascual-Leone, 1974)[10]. Additionally, the authors measure the students' prior knowledge and their achievement in chemistry (in terms of laboratory ability, calculation skills, and acquired

[8] Test of Logical Thinking – TOLT: is a paper and pencil test that assesses the formal reasoning skills, in other words it measures the ability to identify and follow patterns/rules, and it depends on Fluid Intelligence; it the test consists of 10 items evaluating proportional reasoning, combinatorial reasoning, probabilistic reasoning, correlational reasoning, and controlling variables.

[9] Hidden Figures Test: participants are asked to identify and locate in a limited period of time the simple shapes included in a complex figure; the task measure the visuospatial skills

[10] Figural Intersection Test – FIT: consists of 42 items, asking the participants to mark with a small dot the intersections from to up to eight overlapping shapes; this task is considered a measure of the working memory.

knowledge). Their correlation analysis highlighted medium positive and significant values between formal reasoning performance and the three chemical achievements: laboratory ability (r = .36), calculation skills (r = .41), and acquired knowledge (r = .38). Furthermore, the analysis pointed out small positive and significant values between prior knowledge and chemistry achievements (laboratory ability, r = .26; calculation skills, r = .21; and acquired knowledge, r = .23). On the other hand, no significant correlations were found between chemistry achievements and both HFT (visuospatial skills) and FIT (working memory). These findings were further confirmed computing three separated regression analyses. When examining chemistry achievement across specific aspects (laboratory activities, calculation, and acquired knowledge) the authors found that both visuospatial skills and the working memory were not significant predictors of chemistry achievement, whereas formal reasoning skills emerged as the strongest predictor. Other authors, during the same period, reported a significant relationship between these cognitive processes and chemistry learning (Niaz, 1987; Pribyl & Bodner, 1987). Pribyl & Bodner (1987) focussed the attention of the different components of visuospatial skills: Mental Rotation task the Purdue Visualization of Rotations (Guay, 1976)[11] and the disembedding ability with an adaptation of the Hidden Figures Test. The two authors measured whether the university students' performances in an organic chemistry course were related to the visuospatial skills. The research involved students from different degree courses (such as agriculture or health science, biology and professional students, chemical engineering, and pharmacy or medical chemistry). The authors observed small and medium positive significant correlations between exam performance and disembedding skills Pearson's r values [0.18-0.39]. Whereas mental rotation skills were found significantly correlated to final exam scores in the agriculture or health science and in the pharmacy or medical chemistry courses. Overall, the authors concluded that a main effect of the visuospatial skills was observed when students were asked to manipulate 2D molecular representation as well as to deal with problem-solving tasks. On the other hand, Niaz (1987) investigated the performances of undergraduates students in chemistry problems with increasing levels of M-demand, defined as the amount of cognitive resources that the person has to simultaneously activate to execute the task. In other words, it indicates the number of unit that the working memory is asked to process at the same time. The author assessed students' working memory using the Figural Intersection Test FIT (Burtis & Pascual-Leone, 1974), their visuospatial skills with the Embedded Figures Test (Witkin, 1971)[12], and their formal reasoning skills using the Lawson Classroom Test of Formal Reasoning (Lawson, 1985)[13]. The analyses showed that students with high scores in the three cognitive tasks performed better in the chemistry tasks. Additionally, their performance in the

[11] Purdue Visualization of Rotations: participants observe a target abstract figure and have to select from four alternatives the two that represent a rotated version of the target stimulus.

[12] Embedded Figures Test (EFT): the present task asks the participants are presented with a complex picture/figure and they have to find a simple geometric shape that is concealed within the larger image

[13] Lawson Classroom Test of Formal Reasoning: this test assesses students' abilities across six core dimensions of scientific reasoning: conservation, proportional reasoning, control of variables, probability, correlation, and hypothetical-deductive reasoning. Participants are presented with a series of demonstrations or problem scenarios in which they are asked to find the correct solution or answer, providing justifications for their choice.

chemistry problems decreased when the tasks' M-demand increases, suggesting a relevant role of working memory in promoting students' academic success in chemistry.

This relationship between problems M-demand (load on working memory) and cognitive processes was further investigated by Tsaparlis and colleagues (Stamovlasis & Papageorgiou, 2012; Stamovlasis & Tsaparlis, 2001, 2012; Tsaparlis, 2005; Tsaparlis et al., 1998) the authors replicated similar results in different age groups that were tested starting from 11-grader children up to first-year university students. In the different studies they measured students' working memory (using backward digit span task[14], sometimes adding Figural Intersection Test), disembedding ability, and logical thinking ability (or in some cases the formal reasoning ability). Overall, the results lead to the conclusion that working memory plays a crucial role in chemistry problem solving tasks, especially when students have to deal with complex ones requiring multiple steps and to process simultaneously various information. It has been reported that working memory can give significant support especially in the execution of complex chemical problems related to organic synthesis, asking students to handle and process multiple information (Stamovlasis & Tsaparlis, 2001) and in particular, when the task to activate more steps to be solved (Tsaparlis et al., 1998). According to these authors (Stamovlasis & Tsaparlis, 2012) working memory overload can be better understood taking into consideration the logical thinking and the visuospatial skills (e.g., disembedding): when these skills are weak may inhibit the overall working memory efficiency. This conclusion observed in high school students is consistent with the finding emerged in younger students (6^{th} grade). The differences in two tasks, assessing the ability to understand and describe chemical changes, is partially explained by logical thinking ability (LG) and by visuospatial (VIS) skills (Stamovlasis & Papageorgiou, 2012). The regression analyses pointed out that the two cognitive processes are significant predictors of both describing (LG: $\beta = .45$, $p < .001$; VIS: $\beta = .23$, $p < .05$) and understanding (LG: $\beta = .46$, $p < .001$; VIS: $\beta = .29$, $p < .01$) performance. This has been confirmed in university students too (Tsaparlis, 2005). The author explored the relationship between final exam performance and the two components of working memory: using the backward digit span to measure their ability to handle and manipulate verbal information, and the Figural Intersection Test that loads more on visuospatial components. The study collected students' data from January 1995 up to February 1997, and it emerged, combing the Pearson correlations coefficient, that verbal components play a weaker role ($r = .17$, $p<.05$) compared to the visuospatial ones ($r = .31$, $p<.001$). The pivotal role of visuospatial working memory components in chemical problem-solving tasks was recently confirmed by Upahi et al. (2020). Over 600 university students took part in the investigation, measuring visuospatial working memory components (Figural Intersection Test – FIT) and students' ability to solve chemical problems. The correlational analysis showed that the scores in the cognitive task and the student performance at the chemistry test were strongly and significantly related, $r = .81$, $p < .010$. Overall, what emerges from this literature is that working memory, especially visuospatial components, plays a crucial role when students are asked to execute a chemical problem. The correlational values may vary, but they all lead to a similar conclusion. The differences depend

[14] Backward Digit Span task: participants hear a series of digit in a random order, and must recall them in reverse order, starting with the final digit and continuing back to the first.

partially on the fact that different samples of students are compared, and the chemical problem tasks are usually ad hoc instruments, designed specifically for a particular study.

However, in the chemistry education field we face a further challenge: the cognitive processes activation and contribution during the execution of a task (testing students' understanding and chemistry) may be different according to the topic or the specific task. The literature briefly reported here is majorly related to problem solving task, but we can have chemistry problem requiring more reasoning (open-ended) or in other cases (for example in physical chemistry tasks) the calculation skills are mainly involved (Overton & Potter, 2011; St Clair-Thompson et al., 2012). Both studies, that involved university students, recognized that open-ended problems performance is related to different cognitive aspects compared to the physical chemistry ones (algorithmic problems). Overton and Potter (2011) observed that the disembedding scores (visuospatial skills) were related to the open-ended problems ($r = .27$, $p < .01$), but no significant relationship was found for the algorithmic ones. Later, St Clair-Thompson et al. (2012) reached similar conclusions observing a significant correlation between verbal and visuospatial components working memory tasks (requiring to recall and process information) and open-ended chemical problems, $r = .27$, $p < .05$ and $r = .24$, $p < .05$. respectively. The same tasks are negligible related to algorithmic problems; furthermore, both chemical problems (open-ended and algorithmic) have been found weakly and not significant related to pure recalling working memory tasks (such as digit or block recall task)[15], $r = [.00 - .20]$. Consistent findings were reported more recently by Vilia et al. (2017), investigating 470 9-graders students (mean age 14.33 years old, SD = 0.58).The authors were interested in exploring whether different types of reasoning are related to students' academic achievement in a physical-chemistry course. The participants were asked to execute all the tasks included in the Reasoning Test Battery (Almeida & Lemos, 2006). The battery measures the students' reasoning ability with different tasks assessing multiple reasoning skills: numeric (NR), verbal (VR), spatial (SR), abstract (AR), and mechanical (MR). NR and SP are simple pattern tasks[16] that require to deal with digit or visual (geometrical shape) stimuli, respectively. VR and AR, instead, are advanced pattern tasks:[17] the first using words and the second pictures. Finally, the MR includes different short real-life problems, requiring the child to properly solve them. The results pointed out that academic success in physical-chemistry (replicating the study at first, second and third term) was significant correlated with all the five types of reasoning, but the values were higher with NR problems $r = [.31 - .37]$, and VR problems $r = [.35 - .37]$, compared to SR problems $r = [.28 - .30]$, AR problems $r = [.24 - .30]$ and MR problems $r = [.17 - .21]$.

[15] Recalling working memory tasks: it refers to cognitive tasks that ask the participants to recall a set of verbal (digit or word) or visual (blocks or pictures) stimuli in the same order/sequence they have been presented. According to Cornoldi and Vecchi (2003; see also Richardson & Vecchi, 2002) it is possible to discriminate between: passive working memory tasks, requiring simply to handle and then recall information; active working memory tasks, asking the person an additional manipulation and updating. The first load is mainly on phonological loop and on visuospatial sketchpad; whereas the latter stresses more on the central executive components.

[16] Simple pattern tasks are all those tasks requiring the participants to recognize and extend a given sequence, identifying the rule that links the elements in the given sequence.

[17] Advanced pattern tasks: all those tasks requiring the participants to identify the abstract core explaining the relationship between elements; compared to the simple pattern tasks they are more complex since they ask the participants to analyse and manipulate in a more challenging way the stimuli.

Sorby et al. (2020), further investigated these differences in cognitive processes according to the type of problem. They provided an interesting argument illustrating how the combination of visuospatial and working memory skills can explain individual differences in learning performance. They investigated the relationship between chemical problem-solving performance and visuospatial skills among undergraduates enrolled in a 3rd year course in chemical engineering (thermodynamics course). The authors assessed students' visuospatial skills with a task measuring intrinsic-dynamic components (asking them to mentally represent and manipulate abstract geometrical shapes), and the chemical performance using 12 problem-solving tasks related to mass-balance (four of which include stoichiometry too). The first valuable result is that in some problems the visuospatial skills were not significantly related to students' performance; however, there was a single problem where visuospatial skills seem to be relevant. This problem was not more demanding compared to the other, but it did contain numerous linguistic and semantic elements. This task places a greater burden on working memory resources, and students with higher visuospatial scores performed better. The authors hypothesised that they easily externalize (e.g., drawing or mentally imaging the molecular models) the representational components included in the problem, reducing the working memory overload. In summary, it emerges from this literature that different domain-general cognitive processes are activated during a chemical problem-solving task, and this depends on the specific topic that it has been investigated and, on the tasks' structure. For example, Duffy et al. (2020) observed that visuospatial skills are engaged differently when solving mathematical problems, which depends partly on how the problem is presented and consequently represented mentally. Therefore, it is reasonable to hypothesise that a similar thing occurs when dealing with chemical problems.

The majority of literature focussed on chemical problem solving, since this ability can be crucial in chemistry learning; however, as discussed in section 1.2, another important aspect is that the understanding of concepts requires thinking them through the three levels of reality – micro, macro, and symbolic. Therefore, there are some studies in literature (e.g., Huang & Liu, 2012; Stull et al., 2012) that explored the relationship between visuospatial skills and students ability to deal with sub-microscopic or with symbolic level. Huang and Liu (2012) implemented a research study among university students, trying to comprehend how mental rotation competence is related to individual skill in identifying 2D and 3D chemical structural representation. The students were presented with two 2D or 3D representations (each trial) and they should recognize when the two sketches/drawings were identical. In half of the trials the drawings were chemical structures (2D or 3D molecular representation), and the other half they were exposed to 2D or 3D geometrical shapes. The authors measure students' response accuracy and time and collect qualitative information about the strategies implemented using a semi-structures interview. According to students' performance in the chemical task, the authors recognize students with high (N =9; accuracy > 73%) and with low (N= 9; accuracy < 27%) scores. The low score group performed worse (in terms of accuracy) when dealing with chemical structures (both 2D and 3D), and with geometrical shapes (3D only). The response time was similar between the two groups, and there was only a significant difference in the 2D chemical structure trials – the high score group had a major response time compared to the low score group. The authors interpreted this result as a consequence of the implementation of

mental rotation also when handling 2D representations. This was further confirmed with the semi-structured interviews. In summary, this investigation leads to interesting conclusion: the identification of 2D chemical structure is more accurate when students employ mental rotation skills; students in the high score group used different and more effective strategies when dealing with 2D chemical structures than with 2D geometric figures because they understood that the former were projections of 3D models (Huang & Liu, 2012). In the same year, Stull et al. (2012) investigated the university students' capacity to generate different symbolic representations of molecular structures, and how this is related to mental rotation skills. They replicated the study three times, using the same task, which involved solving multiple diagram translation problems. In other words, they were presented with a symbolic representation (Dash-Wedge, Newman, or Fischer) and they had to translate it into a different one (for example, Dash-Wedge to Newman and vice versa, or Newman to Fischer and vice versa). In study one the authors observed the drawing accuracy was positively and significatively related to visuospatial skill (mental rotation), $r = .58$, $p = .001$. In study two and three this value was lower ($r = .32$, $p = .010$ in both studies) because the students' visuospatial competence was partially compensated since they were given a 3D model ball-and-stick. Overall, these findings highlight the relevant role of the visuospatial skills in chemistry education, especially when students are challenged to work with sub-microscopic and symbolic levels of reality, since it means to deal with abstract concepts (symbolic or graphical representation of elements that are not directly observable).

Finally, there are other precious contributes coming from recent literature (e.g., Hodgkiss et al., 2018; Li et al., 2020; Nedungadi & Shenoy, 2023; Nolte et al., 2024; Rhodes et al., 2016; Romero et al., 2024). Hodgkiss et al.(2018) explored how visuospatial skills are related to science achievement in primary-school students (7th to 11th grade). They measure multiple visuospatial components: intrinsic-static, using a children version of the embedded figure task; intrinsic-dynamic, adjusting the mental rotation task (using monkeys instead of abstract geometrical figures), and the mental folding[18] test to this age; extrinsic-static, with a spatial scaling task[19]; extrinsic-dynamic task, using a photo spatial perspective taking task[20]. The authors reported that the accuracy in the chemistry questions of the science knowledge test was significatively related to mental folding task ($r = .21$, $p = .05$), embedded figure task ($r = .23$, $p = .05$), and spatial scaling task ($r = .23$, $p = .05$). Li et al.(2020), instead, moved the focus on executive functions, using the task-switching[21]. The correlational analysis showed that the performance in this task was significantly related to chemistry achievement ($r = .23$, $p < .05$). These findings are partially consistent with results previously reported by Rhodes et al. (2016)

[18] Mental folding test: the person is asked to mentally fold a piece of paper, without the physical action.

[19] Spatial scaling task: in the present study, children look at four treasure maps on a computer screen, each showing a black square in a different location. They are presented with a printed treasure map on a bigger scale, and they have to recognize among the four alternatives on the screen in which one the black square is located in the same position.

[20] Photo spatial perspective taking task: two minifigures with cameras were positioned beside two objects arranged on a table. Children were shown four photographs showing the objects from one character's viewpoint and asked to determine which character had taken the picture.

[21] Task-switching: participants have to match a figure located at the top of the screen with one of two alternative figures presented in the lower corners. At the start of each trial they are presented with a verbal cue, specifying the dimension that should be used as the basis for the match (e.g., color, shape).

that investigated the relationship between chemistry performance and executive functions. In this study, the authors assessed a sample of 7^{th}-8^{th} grade children with a chemical test that included conceptual questions (requiring the children to actively solve a problem using the information learned in the class). In addition, they measured children' working memory, planning ability, inhibition and attention set-shifting. The correlation confirmed that students' accuracy in conceptual questions was significantly related to working memory ($r = .43$, $p < .01$), and to planning task performance ($r = .28$, $p < .05$). So far, the studies that have been carried out included primary or middle school students, but interest in undergraduate students has also grown recently. For example, Nedungadi and Shenoy (2023) investigated university students' performance in a chemistry test, assessing their knowledge of some primary concepts of organic chemistry. Students were also assessed with a standardized battery measuring multiple cognitive aspects: fluid intelligence; crystallized intelligence; visuospatial skills; working memory competence; long-term retrieval ability (collecting information in the long-term memory and being flexible in recalling them); cognitive processes speed (measuring how quickly and fluently a person is able to solve both easy and complex tasks). The correlational analysis showed that students' performance in the organic chemistry knowledge test was significantly related to: crystallized intelligence ($r = .45$, $p < .001$); working memory ($r = .30$, $p < .05$); and long-term retrieval ability ($r = .40$, $p < .01$). The other processes were weakly and not significantly related: fluid intelligence ($r = .25$, $p = .079$); visuospatial skills ($r = .16$, $p = .265$); and cognitive processes speed ($r = .16$, $p = .197$). Similar results were reported by Romero et al, (2024) that measured students' academic success in different disciplines. The authors assessed 120 students that were attempting to access university with a behavioural computerized test measuring students' time management abilities and with a fluid intelligent task. Additionally, they collected students' final college grade as an index of their academic success in multiple disciplines. They observed that the final chemistry grade was significantly related to time management skills ($r = .24$, $p < .05$) but not to fluid intelligence ($r = .01$, not significant). These findings highlight that chemistry understanding, measured as the final college grade, may be to not the best indicator of chemical learning as there are multiple factors that can impact on explaining individual differences such as for example multiple chemical arguments involved in students' science college curricula. Therefore, studies investigating chemistry learning in a more effective way reported more useful results in terms of educational implication. For example, Nolte et al. (2024) conducted a cross-disciplinary study exploring the impact of visuospatial skills. More precisely, they assessed a sample of first-year university students with a content knowledge test (including also specific chemical questions) and with two cognitive tasks: one assessing reasoning and the other the visuospatial skills. The correlational analysis revealed that chemistry knowledge test scores are more related to visuospatial skills ($r = .42$) compared to reasoning skills ($r = .20$). They also observed that in chemistry, similarly to other scientific disciplines, the visuospatial skills have a crucial role beyond the reasoning ability.

In conclusion the relationship between chemistry and domain-general cognitive processes has been widely explored in literature. However, the complex nature of chemistry, as well as the multiple aspects that are included, makes the act of systematically synthesising the literature extremely challenging. The visuospatial skills and working memory are the most studied

domain-general cognitive processes in relationship to different aspects of chemical discipline. The former is mainly in association with the students' ability to deal with the sub-microscopic level of reality and the latter one with the problem-solving abilities. Nevertheless, there are questions that are still open in literature and that require further investigations. For example, how are the verbal and visuospatial components of working memory involved when students are challenged to manage with the sub-microscopic level of reality? Furthermore, another crucial element is that the majority of the studies in literature investigates students with typical development, whereas little is known about students with learning disabilities or special needs education. Hence, it urges to expand the present literature taking into consideration how the different cognitive processes are related to these students' chemical understanding/learning.

1.5 Visualisation tools and chemistry learning

The research project that will be presented in the following chapter included also some experimentation investigating whether the introduction of visual tools may positively impact on students' understanding of chemical concepts (requiring to deal with sub-microscopic level of reality). Therefore, this final section of the chapter gives an overview about the literature that investigated a similar topic to provide the theoretical framework that guided our research project.

The understanding of chemical concepts requires that students generate mental representation or visualisation of elements that are not directly observable, and as Johnstone (1991, 1993, 2010) have claimed students who are less able in dealing with the sub-microscopic level and in moving through the three levels of reality have worse learning outcome in chemistry. Additionally, students presenting difficulties in translating 2D chemical images into 3D molecular representation as well as and in dealing with them have lower visuospatial skills compared to those who succeed in these tasks (Huang & Liu, 2012; Wu & Shah, 2004) Consequently, the introduction of visualization tool might be advantageous and help weaker students supporting their visuospatial skills (Ardac & Akaygun, 2005; Burewicz & Miranowicz, 2002; Stieff, 2011). The term "visualization tool" can be used to describe various types of visual instruments that can support the teacher's explanation such as physical model of particles (ball-and-stick models are the most common), fixed or dynamic/animated computer models, asking the students to actively generate drawing etc. (Williamson & Jose, 2009). However, for some other authors (Stieff & Ryan, 2013) the word visualization refers to "any virtual environment that represents dynamic interactions of sub-microscopic (or subatomic) phenomena". More recently, thanks to technology development, immersive virtual reality has been included as part of the multiple visual tools that teachers can use to facilitate students' understanding (Won et al., 2019). Overall, evidence in literature are still contrasting (Castro-Alonso, Wong, et al., 2019; Stieff & Ryan, 2013). Some studies concluded that the introduction of visual tools can provide positive effects in terms of students learning especially when they provide a support in mentally visualize sub-microscopic-level structure (Ardac & Akaygun, 2005; Linn et al., 2006; Stieff, 2011). On the other hand, there are some authors (e.g., Castro-Alonso, Ayres, et al.,

2019; Schnotz et al., 1999) who pointed out that in some cases they do not lead to a better learning outcomes. For example, students self-perceived higher cognitive load when they were asked to deal with short animation (or dynamic model representation) compared to static model representation (Castro-Alonso, Ayres, et al., 2019). Given the complexity of this topic, it is crucial to dissemble the multiple elements, in order to achieve a better understanding of the multitude of literature concerning the role of visualisation tools. We will give a brief overview of what are the evidence in literature regarding the different visual instruments that teachers can implement in their classes.

One of the most common, because it can be easily employed also in the classroom (without any particular instrument), is the introduction of the physical models. In literature (e.g., Nicoll, 2003; Schiltz & Oliver-Hoyo, 2012; Talley, 1973) there are different studies demonstrating the positive effect of using physical models. For example, Talley (1973) investigated whether the introduction of ball-and-stick models throughout the semester would positively affect the students' performance. The author observed that the ball-and- stick models performed better on a general chemistry assessment, and they were more able to visualize concepts. Furthermore, it has been shown that more positive outcomes emerge when students build and directly manipulate their own models (Nicoll, 2003; Schiltz & Oliver-Hoyo, 2012; Talley, 1973). The qualitative study implemented by Nicoll (2003) highlighted the importance of using ball-and-stick representational models also in higher levels of education, they represent an opportunity to better understand and to discuss the mental representation of chemical sub-microscopical structures. Additionally, they help students in correcting misconceptions and erroneous mental representation. A similar conclusion was reported by Schiltz & Oliver-Hoyo (2012) who investigated how including physical models during the execution of a problem-solving task in inorganic chemistry have positive effects on students' concepts understanding. The authors conclude that providing students with material need to build physical models supported them in visualizing and deeply understanding concepts.

Another widespread visualization tool is the computer model of molecular structures, and it can be fixed (static) or animated (dynamic). The former are graphical representations of molecular structures included in specific computer programs, allowing to visualize the relationship between atomic or subatomic particles. In some studies (e.g., Barnea & Dori, 1999; Dori & Barak, 2001) it has been demonstrated that the use of computer models can be more effective than ball-and-stick. The group of students that used the computer models reached a deeper understanding of bonding and structure of matter, and they also improved significantly, after the didactical intervention, their visuospatial scores (Barnea & Dori, 1999). A similar finding was reported by Dori and Barak (2001) who investigated the role of computer models in promoting the understanding and sequent implementation new concepts, such as isomerism and functional group. The student that used the computer models were more efficient and correct in transforming 2D into 3D molecular representations. The finding led to the conclusion that combining computer and physical models can bring potential advantages in students' model perceptions as well as geometrical and structural comprehension of molecular structures. The use of the static molecular representation of sub-microscopic level, can bring more effective understanding of chemical phenomena observed at macroscopic level and explained using the

symbolic one, as demonstrated by Bunce and Gabel (2002). Similar findings were recently confirmed by Marpaung et al. (2020) who demonstrated that introducing 3D molecular representation can positively affect students' achievements.

In parallel, it has been studied the effectiveness of introducing dynamic or animated representation, short videos that are projected during class or that can be individually viewed by students on their personal device (smartphone, laptop or tablet). Employing dynamic molecular representation have been found to bring positive effect in chemical learning (Akaygun & Jones, 2013; Ardac & Akaygun, 2005; Castro-Alonso, Wong, et al., 2019; Ploetzner & Lowe, 2004; Russell et al., 1997; Suits & Sanger, 2013), but it has also been observed that students exposed to animated models self-perceived higher level of cognitive load compared to those in the control condition (Castro-Alonso, Ayres, et al., 2019). A recent meta-analysis (Castro-Alonso, Wong, et al., 2019), considering the cross-disciplinary effect of static vs. dynamic visualizations, concluded that overall dynamic visualizations bring better learning outcomes compared to static ones. Furthermore, the authors observed that there were two significant moderators: gender and level of education. The effect-size was found to be stronger when the sample included mainly men as well as it was stronger among primary school samples than middle school ones than for university ones. On the contrary, visuospatial skills were similarly related to dynamic and static visualization. Finally, it emerged that the dynamic visualisation effect was stronger in scientific education. This last result was consistent with what was detected in a previous meta-analysis (Berney & Bétrancourt, 2016) focussed on investigating whether the enhancing effect of dynamic visualisation can vary among the various scientific disciplines. The analysis showed that there were multiple significant moderators such as how the verbal information accompanying the animation are presented (the effect of dynamic visualization was stronger when no additional textual information is given or when they are narrated – loading on auditory system), and the different institutional domain (natural sciences, chemistry and biology). The findings showed a medium significant dynamic effect in chemistry, these because employing animation can promote chemistry understanding when students are dealing with sub-microscopic level (Stieff, 2011; Stieff & Ryan, 2013) as well as when the instructor helps the students in creating a meaningful integration of the information (Kelly & Jones, 2008). For example, Ardac and Akaygun (2005) investigate a sample of 8th-grade children exploring whether their learning outcomes during a chemistry class varies in the following three conditions: 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). Overall, a significant difference between static vs. dynamic visual tools emerged (students in the static condition performed worse). The topic in this study was the changes in matter, so the group in the static condition were presented with images that are not able to fully depict the phenomena that are happening at subsub-microscopic level; hence, they have to mentally represent and elaborate what is statically presented on the screen. On the contrary, students in the dynamic group (both individual and collective) were more accurate, suggesting that the animations supported them in generating an integrated (macroscopic and sub-microscopic levels) understanding of the phenomena (Ardac & Akaygun, 2005). Furthermore, the authors observed that this integration seems to be more effective when students are in the dynamic-individual condition.

In literature (Williamson, 2011) another valid instrument that can be used to promote students' comprehension of the sub-microscopic level is the drawing or self-generated graphical representation of molecular models. When students have to actively draw a molecular model, they need to recall their own mental representation, and these can have positive effects on students' understanding (Milne, 1999; Schank & Kozma, 2002), and similar effects were observed introducing computer self-generated model (Williamson et al., 2013). For example, Devetak and Glažar (2010) reported that formal reasoning partially explains individual differences in drawing sub-micro representations. These findings are consistent with those that emerged from a qualitative research (Chang et al., 2014), which demonstrated the positive effect on students' understanding of being actively engaged in a didactic task that requires them to generate computer models (static and dynamic). The authors claimed that these activities support students in developing a more integrated comprehension, and this was more evident in the group that self-generated the dynamic visualizations. Finally, a more recent investigation of Cooper et al. (2017) confirmed that sketching activities can be easily integrated into regular chemistry classes and that they can enhance model-based reasoning.

The last visualization tool that is presented in this section is the Immersive Virtual Reality (VR) developed thanks to the recent technological progress. This visual tool can have a positive effect in terms of chemistry learning (Limniou et al., 2008). The participants were presented with two different molecular representation 2D models (on computer screen) and 3D animated models (designed for a fully immersive VR environment). The 3D animated condition (in the immersive VR environment) has been shown to enhance students' comprehension of molecular structures and structural changes during chemical reactions and to improve students' engagement and motivation towards learning. The greatest advantage of using immersive VR environments is that students can physically manipulate (grabbing, and rotating) the molecular model, actions that are not possible using any other visualization tool (Won et al., 2019). Furthermore, technological improvements have provided us with very efficient devices allowing us to experience more realistic, interactive and affordable experiences (Won et al., 2019). Despite the positive aspects, it should be noted that dealing with 3D representation into an immersive VR environment might be overloading (Ainsworth, 2008; Keller et al., 2021; Ploetzner & Lowe, 2004). It has been found (Lowe & Boucheix, 2017; Schwan & Papenmeier, 2017) that when students have to learn a complex and unfamiliar (new) topic, the use of dynamic 3D visualizations with the proper conceptualization might generate misconceptions or reinforce incorrect understandings of concepts and phenomena. Therefore, Won et al. (2019) identified and summarized the key elements necessary for creating an effective immersive VR environment, that can promote functional learning experiences. These elements are: creating a collaborative learning context, where students are encouraged to share and cooperate in knowledge construction, and guiding students during the environment exploration by giving them activities coherent with the learning goal. Similar conclusions are reported by van Dinther et al. (2023), the authors claimed that effective immersive VR learning experiences can be developed following the four key elements of meaningful chemical education. These are: connecting the theoretical explanation with everyday life; offering students a clear rationale for the relevance of learning a specific topic; allowing the students to play an active role; supporting students in generating interconnection between observable and intangible aspects (macroscopic

and sub-microscopic). The authors concluded that immersive VR could represent a precious teaching resource, able to generate meaningful learning experiences and to increase students' interest towards the discipline. Another investigation is the one implemented by Edwards et al. (2019). The authors used an immersive VR environment where students have to use natural hand motions to build molecules and to comprehend molecular structures and boding. Overall, it emerges that this visual tool promotes students' engagement, motivation, interest as well as organic chemistry learning. Consistent findings were observed also with the introduction of a more technological advanced tool like the augmented VR (C. H. S. Wong et al., 2021). The Augmented VR (AVR) belongs to the immersive VR technologies, but it offers a learning experience more integrated within the real world. AVR is characterized by an overlap between digital 3D computerized models and the concrete world surrounding the person that is involved in the learning experience. The immersive experience is only partial because participants have a solid perception of the real world, but on the other hand is a more affordable visual tool, since it does not necessarily require specific devices, but can easily be implemented with a smartphone or a tablet.

In summary, this brief and not exhaustive literature overview it can be concluded that the multiple visualization tools (such as physical models, fixed and animated computer models, student-generated drawings or animations, immersive VR) can be precious instruments to promote students understanding of chemical topic, especially those requiring to deal with sub-microscopic level. However, findings in the literature are not always consistent, as the efficacy of these tools depends on individuals' cognitive differences and may vary in the different chemistry domains. Nonetheless, evidence demonstrated that teachers can obtain positive effects in terms of learning, implementing them during their classes, integrating them with the other activities and providing the students with the proper contextualization. Overall, it seems that dynamic animation models are the most widely used also among young students (middle school). Furthermore, they have been in the spotlight since they are widely used in multiple disciplines, and few meta-analyses have concluded that the use of dynamic visual tools has more effective positive consequences on students learning compared to the static ones. However, there are no investigation in chemical education that explores whether the introduction of these visualization tools can influence academic success among students with learning difficulties. All the literature presented so far focusses on students with typical development. Further investigation is needed to determine whether the implementation of dynamic animations could improve students' understanding of sub-microscopic concepts. Finally, the majority of the studies are focused on testing learning outcomes without considering the cognitive processes involved. Future investigations should consider relationship between the use of dynamic animations and domain-general cognitive processes.

Chapter 2: Undergraduates with Specific Learning Disabilities (SLDs)

2.1 Introduction

In recent years, both national and international research have reported that the number of students with Specific learning Disabilities (SLDs) enrolled at university has grown (ANVUR, 2022; Del Tufo & Earle, 2020; Newman et al., 2011).In the Italian context, for example, it has registered an increased number of students with a certified diagnosis of SLDs, in accordance with the Law 170/2010 (Legge 10 ottobre 2010, n. 170, 2010), see Figure 2.1.

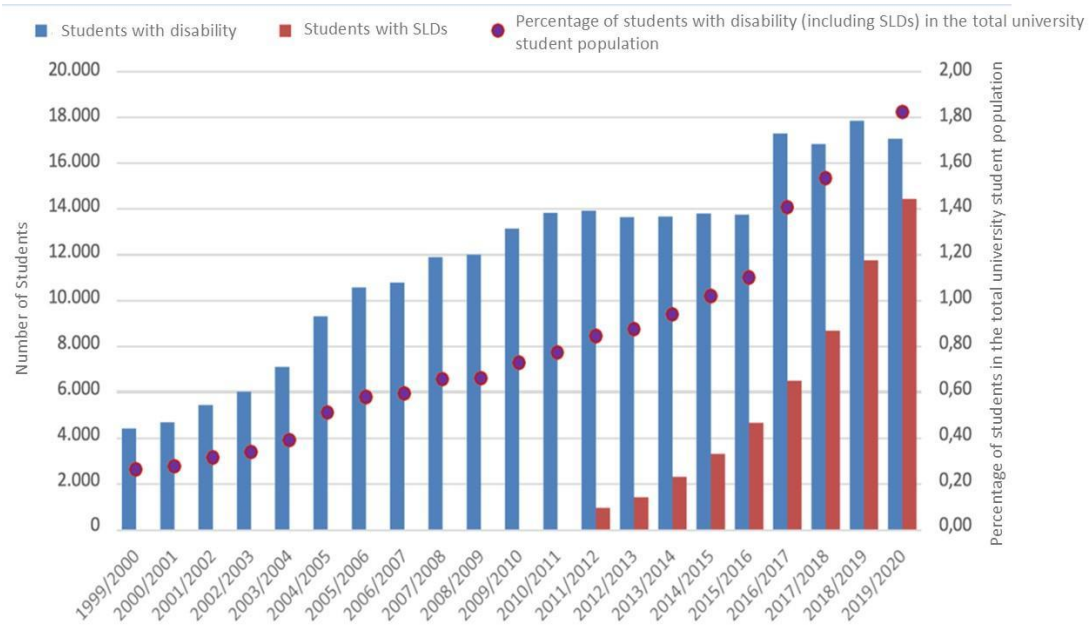


Figure 2.1 Graphical representation showing the increased number of students with SLDs enrolled at university (in red), that is almost equaling the number of students with disabilities (in blue) – (ANVUR 2022, p. 22)

Specific learning disabilities (SLDs) can be defined as neurodevelopmental disorders implicating difficulties in the automatization of reading, writing and/or mathematical abilities, caused by neurobiological issues (American Psychiatric Association, 2013). The difficulties

can be in a single domain, like reading (dyslexia), writing (spelling[22]: dysorthography; handwriting[23]: dysgraphia), mathematics (dyscalculia) or in multiple domains (mixed) (American Psychiatric Association, 2013; Legge 10 ottobre 2010, n. 170, 2010). These difficulties affect students' academic success and can negatively affect students' well-being and their scholastic self-esteem (Casali et al., 2023; Matteucci & Soncini, 2021). These difficulties typically emerge in the early years of education and persist across the lifespan (American Psychiatric Association, 2013).

The increased number of students with SLDs enrolled at university, especially at scientific degree courses, call for more research focussed on investigating what kind of tools can be implemented to support undergraduate students with SLDs in learning science. The number of studies that investigated university students with SLDs and science learning is still scarce, and it is even more incomplete when we try to focus the attention on chemistry learning. However, the majority of scientific degrees include in their curricula at least one general chemistry course. Dealing with this discipline can be even more complex for students with SLDs, because their cognitive processing abilities are different compared to their peers with typical development. In fact, it has been demonstrated that students with SLDs perform significatively worse in verbal working memory tasks (Daniel et al., 2022; Pizzigallo et al., 2023; Toffalini et al., 2017), in other words their working memory related to linguistic material is less efficient and this might compromise their chemistry learning. In the present chapter we will provide a brief overview of the main characteristics of SLDs and how they manifest during adulthood. Secondly, we will also discuss the main challenges that students with SLDs face when they enrol at university, as well as the main services that are offered in the Italian context. Finally, we will conclude with a summarization of the main struggles they deal with during learning experience, including an in-depth analysis about science education. The main goal of the present chapter is to give a general introduction to the topic of learning disabilities.

2.2 Specific Learning Disabilities (SLDs)

The label Specific Learning Disabilities (SLDs) indicates a set of developmental disorders emerging as a specific difficulty in one or more of the following domains: reading, writing (spelling and handwriting), and mathematics (American Psychiatric Association, 2013). These persistent difficulties impact students' academic achievement at all educational levels, contributing to a more challenging learning experience. According to manuals (American Psychiatric Association, 2013; World Health Organization, 2018) learning difficulties in one or more domains can be classified as SLDs only when students' struggles in automatizing reading, writing, and/or mathematical processes cannot be explained by other factors: other

[22] Spelling: it can be defined as the set of cognitive processes activated to write a heard or thought word following the propter orthographic rules of a specific language; therefore, it involves the ability to recall, to recognise, and to mentally represent words (Coltheart et al., 1993; Cornoldi, 2023).

[23] Handwriting: it can be identified as the set of cognitive processes allowing the writer to produce a single or a sequence of graphemes by hand using a pen/pencil or a stylus (Cornoldi, 2023; Pontart et al., 2013).

neurodevelopmental disorders such as intellectual disability, sensory and motor deficits, and other mental or neurological disorders; environmental factors such as sociocultural disadvantage, lack of proficiency in the language or inadequate school education; and emotional factors like for example emotional deprivation or affective problems within the family context. The term SLDs include multiple profiles that the Italian law 170/2010 separates as:

- Dyslexia that refers to a specific difficulty in automatizing the reading processes that allows the decoding of a written text. Students with dyslexia are significantly slower and inaccurate in reading. In general, they are slow readers, and in some cases, they struggle in syllabification (reading the whole word); additionally, they might be less accurate compared to typical development students. The typical errors can be inversions (e.g., "form" instead of "from") or substitutions of graphemes (e.g., "bod" instead of "dog"). In language with transparent orthography[24], such as Italian, inaccuracies are more frequent during early education. Whereas, during adulthood, it is mainly the slowness of reading that persists.
- Dysorthography that manifests as an impairment in writing words accurately due to a deficit in the processes that allows to transform phonemes into graphemes and/or in those that activate the recall of the orthographic representation of a specific word. Usually students struggling in automating this competence make systematic mistakes, such as: switching two graphemes like for example "f" and "v" (both labiodental consonants), "b" and "p" (both bilabial consonants), "t" and "d" (both stop consonants); omitting parts of the word or single letter; inverting single letters or a whole syllable like for example "tehortical" instead of "theoretical". The acquisition of writing skills is complex in each language, even in those with transparent orthography, since transparency is not always true in case of phoneme-to-grapheme transformation (relevant in writing). For example, in the Italian language, the grapheme "q" corresponds to the specific phoneme /k/, but the phoneme /k/ could be transcribed into two different graphemes such as "c" or "q" (e.g., cuoio / kwjo / [leather] or quale / kwale / [which]). Whereas, in other case the two graphemes correspond to two separated phonemes (e.g., cesta / tʃesta / [basket] or quale / kwale / [which]). This because, in Italian, the grapheme "c" corresponds to the phoneme / k / when it is followed by "a", "o", and "u", and the phoneme /tʃ / when it is followed by "e", "i". All these exceptions can be solved recovering the meaning of the word and its orthographic representation in the long-term-memory. Students with dysorthography struggle in dealing with all these processes.
- Dysgraphia, instead, is an impairment related to the peripheral motor system involved in writing by hand. Hence, the handwriting of these students appears illegible and/or dramatically slow. Common manifestations may include poor pen grip (using either excessive or insufficient pressure on the paper); inadequate use of available writing space (difficulty respecting margins and lines and leaving

[24] Language with transparent orthography: they are characterized by a consistent one-to-one correspondence between graphemes and phonemes; meaning that words are read as they are written. Examples of transparent languages include Spanish, Italian, German, Basque, Turkish and Finnish.

inconsistent spacing between letters and/or words); and inconsistency in letter size and shape, with forms often appearing irregular. Finally, these students also have significant difficulty in copying and producing geometric figures, and their drawing skills are often inadequate for their age.

- Dyscalculia is characterised by difficulties in acquiring automatic calculation and/or numerical processing skills. In other words, students with dyscalculia might struggle in: comprehending and producing numerical quantities (for example, they are challenged when they have to estimate the magnitude of numbers or in a task asking to estimate which is the bigger number); recognizing numerical symbols (for example, they can read "1012" as "one hundred and twelve", or during a dictation of numbers they heard "one hundred and twelve" and write "10012" instead of "1012"); performing basic arithmetic operations as well as automating procedures for solving general algorithms (for example, they may exchange sum and multiplication symbols, or they can wrongly set up the numbers during a written calculation task, resulting in a wrong output).

However, all the different profiles presented so far partially share a common set cognitive process. Multiple studies in literature (e.g., Francuz et al., 2013; Mateu-Estivill et al., 2024; Rapp et al., 2016; Semrud-Clikeman, 2005; Temple, 2002) have concluded that deficit in these domains (reading, writing and mathematics) can be related to dysfunctional or deficient activation of some specific brain areas that support reading, writing or mathematical processes, that are partially overlapping. As well as studies on siblings suggested that SLDs can be partially explained by genes (Berninger & Richards, 2010; Bishop & Snowling, 2004; Praet et al., 2013; Shalev et al., 2001; Snowling et al., 2007). For example, Bishop and Snowling (2004) observed that family members of students with dyslexia (significant impairment in reading) performed worse in a reading task compared to a control group (involving people whose family did not include a person with an SLDs' diagnosis). Similarly, Praet et al. (2013) that assessed a sample of siblings of children with dyscalculia during kindergarten (T1) and first grade (T2), they reported that these children performed significantly worse in a number sense task compared to peers without family members with dyscalculia (control group). As well as the former underperform in the procedural and conceptual counting tasks at T1, compared to the control group. Overall, it has been concluded that SLDs are a complex neurodevelopmental disorder that have a multifactorial nature, integrating genetic, epigenetic and factors (American Psychiatric Association, 2013; Georgitsi et al., 2021).

2.2.1 SLDs in adulthood

National and international literature (Hatcher et al., 2002; Kaufmann et al., 2020; Kinsbourne et al., 1991; Pellegrino et al., 2024; Reis et al., 2020; Swanson & Hsieh, 2009; Zamperlin et al., 2024) has shown that SLDs persist throughout the lifespan, although their

manifestations may vary. For example, errors in reading and/or writing may reduce significantly, but adults with SLDs may still be slower compared to their peers because the sub-processes are not automatized. In particular, it has been demonstrated (Shaywitz et al., 2003) that students with SLDs and good general cognitive abilities compensate more effectively. Therefore, their performance (in reading, writing and/or mathematics) can improve throughout education and clinical interventions, but it will not equal that of students with typical development.

It has been demonstrated (Bruck, 1990; Callens et al., 2012; E. Cavalli et al., 2016; Elbro et al., 1994; Gagliano et al., 2015; Olofsson et al., 2012; Re, Tressoldi, et al., 2011; Reis et al., 2020) that adults with certified reading impairment (dyslexia) are slower readers. An Italian investigation (Tressoldi et al., 2001) examined the development of reading speed in a sample of Italian children with dyslexia. The results showed that their reading speed increased at a rate of approximately 0.3 syllables per second per grade (almost half the rate reported for children with typical development, which is estimated to be 0.5). Lami et al. (2008) also found that adults with dyslexia exhibit deficit in phonological awareness, despite a reduction in errors (see also Bogdanowicz et al., 2014; Nergård-Nilssen & Hulme, 2014). They struggle more compared to peers with typical development in reading lists of words or non-words[25]; as well as they are slower and less efficient during silent reading compared to typically developed students (Re, Tressoldi, et al., 2011). Additionally, adults with dyslexia keep struggling with phonological awareness tasks that require to analyse and manipulate phonemes (Reis et al., 2020) such for example: recognising the syllables within a word (e.g., ap-ple); blending different syllables to form a word (e.g., "ba", "na", "na" that becomes "banana"); removing or substituting a phoneme or a syllable, etc. Another persistent difficulty that manifest among adults with dyslexia is for example a weaker performance in rapid automatized naming[26] tasks (Araújo & Faísca, 2019; Bogdanowicz et al., 2014; Nergård-Nilssen & Hulme, 2014; Reis et al., 2020), in other words they are slower in naming familiar objects compared to their peer with typical development. The recent meta-analysis implemented by Reis et al. (2020) showed that adults with dyslexia performance worse than students with typical development on vocabulary tasks, measuring semantic knowledge and pronunciation of words, as well as the ability to interpret the meaning of specific name in a context-dependent manner. Additionally, it has been reported (Re, Tressoldi, et al., 2011; Reis et al., 2020; Silva et al., 2022) that these students struggle in lexical decision tasks, asking them to identify whether a string of graphemes is word or a non-word. Finally, adults with dyslexia (who do not have any impairments affecting their ability to process quantities) still find it difficult to read and write both verbal material and numbers (Cornoldi et al., 2021).

In a similar way, the difficulties in the writing domain (spelling) have been found to be persistent, although the way they manifest may change. Students with dysorthography (significant impairment in automatizing spelling skills) in adulthood still misspell words. In a

[25] Non-word: it refers to all verbal stimuli (a string of graphemes), like a word, but with no meaning, some examples are "bip", "shromp" or "snarge".

[26] Rapid Automatized Naming (RAN): it can be defined as the ability to quickly name aloud a visual familiar stimulus such as colours, numbers, common objects, etc. (Denckla & Rudel, 1976)

language with transparent orthography such as Italian, a study of adolescents (Fenzi & Cornoldi, 2015) found that most errors occurred when students had to write or recognize words that sound the same (homophones), but were spelled differently (non-homographs). For example, "*lago [/ˈla.go/]*" vs. "*l'ago [/ˈla.go/]*" both terms have the same pronunciation, but the in the first case *lago* stand for "lake", whereas *l'ago* means "the needle". Spelling errors are also frequent among adults with dyslexia, especially when they are asked to carry out a writing task that requires articulatory suppression (Re, Lucangeli, et al., 2011; Vizzi et al., 2024). In these tasks students are instructed to repeat continuously an irrelevant stimulus/sound (for example, the syllable "la") aloud while executing a writing task such as a dictation. The double-task (writing and articulation) overload verbal working memory resources in students whose phono-articulatory resources are limited; hence, they struggle in spelling the words properly. Differently, students with typical development can execute both tasks accurately, because the automatization of writing skills implies that they have sufficient verbal working memory resources to deal with both tasks.

Finally, part of literature that explored the persistent difficulties of adults with SLDs focussed on impairments in mathematical domain (dyscalculia). It has been demonstrated (Vigna et al., 2022) that adults with dyscalculia had poorer arithmetical skills in both formal (learning setting) and informal settings (real life setting); in other words they underperform not only in mental and written calculation, but they have difficulties in daily tasks such as estimating time, distances or quantities or managing money. Difficulties in retrieving arithmetic facts persist in adulthood; whereas difficulties in written calculation are less frequent but overall, their execution is lower compared to peers with typical development (Ghidoni et al., 2013, 2015). Adults with dyscalculia are more incorrect and slower than peers with typical development in mental calculation (Bulthé et al., 2018; De Visscher et al., 2017), also in adulthood they experience difficulties executing basic operation like addition, subtraction, multiplication and division (Mejias et al., 2012; Wilson et al., 2015). Additionally, it has been observed that adults with dyscalculia perform worse in numerical estimation task, requiring to judge the magnitude of symbolic (digits) and non-symbolic (e.g., dots) numbers representation (Bulthé et al., 2019; Mejias et al., 2012). Finally, in the Italian context, Montesano and Valenti (2018) investigated adults with dyscalculia and observed findings consistent with the international literature. The authors claimed that these students experience significant difficulties in the various aspects of the mathematical domain: computing mental calculations; executing tasks that engage syntactical knowledge, such as positioning and combining digits to write a number correctly; understanding and using number words (e.g., "one", "two", "one hundred", etc.) in alignment with their corresponding numerical values.

In summary, it is true that reading, writing and/or mathematical skills of people with SLDs can improve, because students can learn strategies that help them in compensating their difficulties. However, these students will not automatize these processes. Consequently, they will never equalize their peers with typical development, and they will manifest symptoms also in adulthood. They may be able to perform accurately, but they will be slower. When they have to face multiple tasks simultaneously their performance in a reading or writing or mathematical task will drop.

2.2.2 Students with SLDs and domain-general cognitive processes impairments the effects of academic success

The investigations that focused on intellectual profile of students with SLDs (De Weerdt et al., 2013; Giofrè & Cornoldi, 2015; Peng & Fuchs, 2016; Toffalini et al., 2017) concluded that these children may also have problems with executive functions, working memory, thinking and reasoning, and processing speed. A recent investigation (Pizzigallo et al., 2023) on adults confirmed that these issues (related to domain-general cognitive factors) could persist through lifespan. The difficulties at domain-general cognitive processes level can be very different among students with SLDs. Likewise, they can exhibit heterogeneous manifestations even within the same domain-specific impaired domain, reading, writing and/or mathematic (Carmichael et al., 2014). These domain-general cognitive impairments as well as the domain-specific ones could represent a challenge for students with SLDs and can negatively affect learning and study experience. Here, we will shortly describe how inefficiency in one or more of these domain-general cognitive processes could weaken students' academic success.

Executive Functions (EFs)

A recent meta-analysis (Lonergan et al., 2019) examined inhibition, switching attention and verbal working memory in children with dyslexia and it pointed out that children with SLDs perform worse compared to students with typical development in tasks measuring these three domain-general cognitive processes. Numerous studies (e.g., Beneventi et al., 2010; Brosnan et al., 2002; Christopher et al., 2012; Conte & Marzocchi, 2020; Faccioli et al., 2008; Gooch et al., 2011; Peng & Fuchs, 2016; Vellutino et al., 2004) have provided evidence that children with SLDs perform statistically worse in inhibitions and shifting tasks. It was also observed that, compared to controls, adolescents with dyslexia are less accurate in sustained attention and inhibition tasks (Moores & Andrade, 2010). Furthermore, recent studies (Grinblat & Rosenblum, 2016; Sharfi et al., 2022; Sharfi & Rosenblum, 2016) have observed that adults with SLDs are less efficient compared to peers with typical development in tasks requiring executive functions. The three studies assessed adults with SLDs using a self-report scale (the Behavioral Rating Inventory of Executive Function-Adult version, Roth et al., 2005) and they all agree on a similar conclusion: adults with SLDs self-reported more difficulties with inhibition, shifting and emotion regulation compared to control group (which included adults with typical development). Particularly interesting is the investigation carried out by Grinblat and Rosenblum (2016) that explored how the inefficiency in the executive function has significant consequences in students' everyday life. The authors in this investigation assessed the sample also with a second scale, the Time Organization and Participation Scale – TOPS (Rosenblum, 2012) aimed at detecting people' difficulties in scheduling daily life tasks on time. The adults with SLDs reported more problems with time estimations, and that they need more time to execute daily tasks. These difficulties have been found to be related to the self-reported difficulties in the EFs. These issues in managing time and planning could have significant

consequences on students' academic success, as well as on their wellbeing because it could interfere with the students' ability to balance study time, with work/free-time activities and social life (Grinblat & Rosenblum, 2016).

Another aspect that has been investigated is the relationship between auditory and visuospatial attention and reading and writing development. For example, Cherry and Kruger (1983) have observed that children with SLDs performed significantly worse compared to their peers with typical development in a selective auditory attention task, especially when semantic distractors were presented. Another investigation on adults (Sterr, 2004) found that auditory attention persist into adulthood: students with SLDs performed significantly worse in various attention tasks. They obtained lower scores also in a task measuring the visual selective attention. In this task participants are asked to pinpoint a set of symbols into a coloured city map within two minutes. Sterr (2004) observed that young adults with SLDs have more problems in processing this complex visual information. These findings corroborate with previous investigation Casco et al. (1998) who observed that among a sample of 11-12-year-olds, those who struggled more with a selective attention task were also slower and more inaccurate readers compared to those who obtained high scores in the visual attention task. Therefore, it has been observed that students with SLDs may exhibit impairments both in auditory and visuospatial selective attention, and these issues persist across the lifespan. Consequently, they might struggle to process complex verbal and visual stimuli including multiple pieces of information, from which they must identify and focus on only the most relevant.

Working Memory (WM)

Among the various domain-general cognitive processes involved in learning, working memory (WM) has been widely investigated (Alloway, 2006, 2010, 2012) and its role remains significant even at higher levels of education, such as secondary school or university (Alloway & Alloway, 2010, 2013). Studies examining the intellectual profiles of students with SLDs (De Weerdt et al., 2013; Giofrè & Cornoldi, 2015; Gontkovsky & Golden, 2022; Nergård-Nilssen & Hulme, 2014; Peng & Fuchs, 2016; Toffalini et al., 2017) have pointed out that most of these students exhibit inconsistent profiles, characterised by a significant decline in performance on verbal WM tasks. A series of interesting Italian investigations (Giofrè & Cornoldi, 2015; Pizzigallo et al., 2023; Toffalini et al., 2017) observed the performance of children and adults with SLDs in various tasks included in the Wechsler Intelligence scale (Wechsler, 2012, 2013). They all found consistent results showing that in many cases the General Ability Index (including two scales: the Verbal Comprehension Index - VCI and the Perceptual Reasoning Index - PRI) was significatively higher compared to the Cognitive Proficiency Index (including two scales: the Working Memory Index – WMI and the Processing Speed Index - PSI). In particular, students with SLDs performed considerably lower in WM tasks compared to how they perform in the verbal and non-verbal reasoning tasks. Liebel and Nelson (2017) investigated a sample of college students with and without SLDs with two WM tasks measuring verbal and visuospatial components, respectively. The authors found that students with SLDs

compared to the control group performed significantly worse in the verbal WM task, but no significant difference emerged in the visuospatial WM task. However, recent findings (Daniel et al., 2022) dthat students with SLDs struggle more than peers with typical development when they are asked to handle and manipulate complex phonological or visuospatial information. This result seems to lead to a different conclusion: that also visuospatial WM components might be weak in students with SLDs. This inconsistency may be due to the fact that different types of SLDs tend to exhibit different cognitive profiles (Toffalini et al., 2017). For example, students with dyscalculia or with impairment both in reading/writing and mathematical domain perform worse than students with dyslexia or dysorthography in perceptual reasoning, in WM and processing speed subtests. The major difficulties experienced by children with dyscalculia when dealing with visuospatial information (PRI) could be explain why it has been reported (Mammarella et al., 2018; Peng et al., 2016) that these students showed impairment both in the verbal and visuospatial WM components. Furthermore, the learning tasks are differently related to WM. For instance, Prevatt et al. (2010) found that WM, in university students with dyscalculia, correlates more with problem solving (r = .44, p< .010) and quantitative concepts (r = .40, p< .010) tasks than with calculation and math fluency tasks, r = .26, p< .010 and r = .29, p< .010 respectively.

In conclusion, it emerges from literature (e.g., Brandenburg et al., 2015; Daniel et al., 2022; Liebel & Nelson, 2017; Mammarella et al., 2018; Peng et al., 2016; Peng & Fuchs, 2016; Prevatt et al., 2010, 2010; Reis et al., 2020) that students with SLDs could exhibit impairment in WM components and this was observed both in children and in adults. These weaknesses might affect students' ability to process information, and together with the domain specific problems (in reading, writing and/or mathematics) they could affect students' learning performance (Okur & Aksoy, 2025; Wang et al., 2025).

Thinking and reasoning

Academic success requires a huge engagement of cognitive resources, especially in high level education setting, since it involves the acquisition of complex concepts, as well as theories and the explanatory hypotheses requiring the combination of two critical and creative thinking (Cherubini, 2021).

Critical thinking has been defined as a high-level cognitive process that entails the activation of multiple skills, such as, judgement, analysis and synthesis based on logical reasoning (Almeida & Franco, 2011; R. T. Carroll, 2000; Halpern, 2007; Sternberg et al., 2007). During an academic learning experience, students engage with the topic by critically analysing concepts through an active approach. Critical thinking supports students in examining the argumentative structure and deepening their understanding of the concepts (Haskins, 2006). Recently, it has been proposed a classification of the multiple phases of critical thinking (Fabio et al., 2025; Fabio & Suriano, 2023):

1. Problem Clarification: this involves identifying the type of problem, isolating its key issue, and relating it to similar known cases to understand it.

2. Analysis: in this phase the problem is broken into its constituent parts, and the person tries to map the relationships between the multiple parts, and to connect them to the main question to understand the problem's structure and the implications.
3. Evaluation: it consists of assessing credibility, relevance, and consistency of the information in a problem, to determine which elements are trustworthy, useful, and coherent for reaching a valid and valuable conclusion.
4. Inference: is the final phase where the person draws the conclusions from available evidence, accounts for the reasoning behind those conclusions, and explores alternative possibilities that might also explain the data or solve the problem.
5. Self-monitoring: this phase is activated throughout the entire process, and it consists of reflecting on the degree of difficulty, monitoring the correctness of one's reasoning, and identifying possible doubts or uncertainties to improve accuracy and confidence.

Therefore, it emerges that the whole process requires a significant amount of cognitive resources, in particular, it places a heavy demand on WM ones. The latter allow to handle and manipulate multiple information at the same time as well as to integrate them together and with the previous knowledge stored in the long-term memory. We have acknowledged that students with SLDs have lower and less efficient WM resources compared peers (e.g., Brandenburg et al., 2015; Daniel et al., 2022; Liebel & Nelson, 2017; Mammarella et al., 2018; Peng et al., 2016; Peng & Fuchs, 2016; Prevatt et al., 2010, 2010; Reis et al., 2020). Consequently, the multiple phases of critical thinking can be very challenging for them, especially when they are required to deal with large quantities of information. In the Italian context, when these students must study for a university exam the number of knowledges they need to understand, learn and integrate is consistently more compared to high-school tests. This means that students with SLDs could struggle in applying critical thinking processes. Nonetheless, a recent investigation (Casali et al., 2023) observed that adults with SLDs do not perceive this difficulty, as their self-reported measure of critical thinking was not different compared to their peers with typical development.

The second crucial high-level cognitive process is the creative thinking, and it is defined as the act of creating original ideas or solutions going beyond the body of known theoretical information (Baker et al., 2001; Simonton, 2018). It entails the ability to explore and investigate multiple and alternative ideas/solution requiring cognitive flexibility[27]. This high-level cognitive process is supported by WM and EFs, that coordinate and manage the flow of information: facilitating the focus of attention on the important elements; inhibiting the irrelevant ones; and shifting the attention from one aspect to another. Furthermore, in literature (Bloomberg, 1967, 1971) the creative thinking has been associated to the field-dependence/independence construct (Witkin, 1965; Witkin & Goodenough, 1977), as the field-independent ability consists of detaching from a dominant perceptual organization and reinterpreting a stimulus by identifying relationships and structures that are not immediately

[27]Cognitive flexibility: it refers to the capacity to adapt and change ideas or strategies within the flow of thought when engaged in executing a problem

evident. A simple example is the ability to identify a simple 'hidden' image within a complex visual stimulus (Witkin, 1971). However, it was observed that students with SLDs compared to peer with typical development perform worse in WM tasks (e.g., Brandenburg et al., 2015; Daniel et al., 2022; Liebel & Nelson, 2017; Mammarella et al., 2018; Peng et al., 2016; Peng & Fuchs, 2016; Prevatt et al., 2010, 2010; Reis et al., 2020), have less efficient EFs (e.g., Beneventi et al., 2010; Brosnan et al., 2002; Christopher et al., 2012; Conte & Marzocchi, 2020; Faccioli et al., 2008; Gooch et al., 2011; Peng & Fuchs, 2016; Vellutino et al., 2004), and tend to struggle more in field-independence tasks (Daniel et al., 2022); hence, we would expect that these issues could negatively affect their creative thinking ability. However, there are consistent evidence in literature, showing that students with SLDs performed better in creative thinking tasks (e.g., Bigozzi et al., 2016; Cancer & Antonietti, 2019; Everatt et al., 1999; Šimčíková, 2018). More recently a meta-analysis (Majeed et al., 2021) showed that studies reporting a significative better performance in the creative thinking among people with SLDs were implemented on adults. In addition, the authors observed that students with SLDs perform better when the creative thinking task was a non-verbal task. These students learn to use non-typical methods to process information in early childhood (Bigozzi et al., 2016), but the impact of adopting these non-conventional strategies/methods accumulates gradually through education and it becomes evident only in adulthood (Majeed et al., 2021). This conclusion is consistent with Cancer and Antonietti (2019) suggesting that creative thinking can be considered an effective compensatory strategy, which is even more developed in university students and adults with SLDs. They use it to cope with the linguistic and verbal difficulties that characterise academic educational settings. Finally, this is coherent with the results of a recent self-report investigation (Casali et al., 2023) where students with SLDs reported higher scores in the creative thinking items, described themselves as more adept at generating original ideas and seeking alternative ways of doing things.

2.3 From high school to university: what challenges do students with SLDs face

In this context we are interested in focusing the attention on university students with SLDs, hence, it is important to outline the main challenges that students have to face when they enrol at university. This section will provide a brief summarization of the main challenge as well as the individual resources that can support students throughout this transition. Finally, it will provide a short description of the services that can be activated by the faculty in order to sustain them during the academic path.

The transition into university is a crucial moment and it represent a turning point involving multiple changes like different context (such as enrolling in a new institution and, for some, moving to a new city and living independently), and a new self-representation as students, involving a more autonomous and self-regulated approach to organizing study time (Coertjens et al., 2017; Pellegrino et al., 2024). In the Italian context (Pellegrino et al., 2024), for example, students are required to balance academic and extra-academic commitments and they are not supervised daily by lectures; the responsibility to attend classes is on them, choosing which and

how many courses to take (attendance is not mandatory for all degree programs, although it is always recommended), and they have to organize their exam session (the number of exams and how to distribute them throughout the year and within the exam sessions).

According to literature (Coertjens et al., 2017; Gale & Parker, 2014) within this transition from high school to university it is possible to identify four phases:

- Preparation: students start to develop the idea of enrolling in university (usually the final year of high school), and during this phase, they anticipate the changes and prepare for them.
- Encounter (or Induction): students begin to orient themselves in the new environment and try to make sense of the new educational setting (first few days or weeks).
- Adaptation: students deal with the new learning demands and attempt to pass successfully the assessment/exam term (first year, but its duration may extend depending on individual adaptation abilities).
- Stabilization: the final phase, reached when students have conformed to the new educational setting and the various learning demands, only minor adjustments are needed.

Reaching the final step (stabilization) can be challenging especially if students' expectations do not correspond to the reality. It has been demonstrated that their anticipations do not totally match the professors' ones (Gorgodze et al., 2020; Hassel & Ridout, 2018). As well as it has been observed that some students have fearful expectations and they reported higher levels of stress, depression, and poorer university adjustment compared to peers whose expectations are positive (Jackson et al., 2000). The mismatched expectations and the higher level of stress and depression could negatively affect the academic performance and lead some of them to abandon the university (ANVUR, 2022; Jackson et al., 2000).

This transition can be challenging for students with SLDs too, because they must adapt to the new learning context that is more demanding and their anticipations do not completely match the reality (Mortimore & Crozier, 2006; Pino & Mortari, 2014). A recent study (Sumner et al., 2021), indeed, observed that students with dyslexia self-reported lower succeed expectations compared to peers with typical development. They are less confident in passing the exams successfully, managing their study time efficiently, verbalizing their doubts to the lecturer, and attending classes fully. Another factor is that students with SLDs face numerous frustrating learning experiences throughout their school years, and these could facilitate the development of dysfunctional attributional beliefs (Stagg et al., 2018; Vacca et al., 2025). It has been observed that students with SLDs self-reported lower level of academic self-efficacy compared to peer with typical development (Casali et al., 2023).

Furthermore, students with SLDs that transit into university have to deal with additional issues including the decision of whether to disclose their diagnosis to the university's inclusion offices for students with SLDs and to their classmate (Cole & Cawthon, 2015; Grimes et al., 2019; Pellegrino et al., 2024). In the Italian context, there are appropriate university office that

provide supports to students with SLDs, especially during the exams (Pellegrino et al., 2023, 2024). However, the international literature (Cole & Cawthon, 2015; Grimes et al., 2019) has demonstrated that some students with SLDs are less willing to contact these office, but this could have a negative impact their academic success as well as their well- being (Pellegrino et al., 2023). The decision to share and discuss their own diagnosis/diagnoses can be problematic for some students, who might be apprehensive about being labelled and stigmatized by peers and professors (Grimes et al., 2019; Haft et al., 2023; Mamboleo, Dong, Anderson, et al., 2020). This apprehension may be exacerbated by previous adverse experiences when requesting academic accommodations (Mamboleo, Dong, & Fais, 2020). Moreover, the topic of labelling and stigmatization relates also to another aspect that is still hugely discussed: what is considered fair or reasonable adjustment to supports students with SLDs (Riddell & Weedon, 2006). Hence, some students, that ask accommodations during exams, are worried that their request might upset the lecturer or their peers, or in some cases they have interiorised that implementing these measures is unfair (Grimes et al., 2019).

2.3.1 Common obstacles faced by students with SLDs and strategies they implement to overcome reading and writing difficulties

In literature there are multiple studies that investigated the obstacles that students with SLDs face at university as well as the most common strategies they implement to cope with them (Howard-Gosse et al., 2024; MacCullagh et al., 2017; Mortimore & Crozier, 2006; Olofsson et al., 2012; Pino & Mortari, 2014; Sumner et al., 2021). The investigation implemented by Mortimore & Crozier (2006), for example, found that the percentage of students with dyslexia that self-reported difficulties in multiple academic aspects was significantly higher compared to peers, such as taking notes (SLDs = 78% vs. control = 18%), managing the study time (SLDs = 66% vs. control = 25%)[28], expressing their ideas orally (SLDs = 24% vs. control = 10%) and in writing (SLDs = 72% vs. control = 11%), and being focused in class (SLDs = 50% vs. control = 17%)[29]. Therefore, it emerges that students with and without dyslexia struggle in adapting to the new learning context, but this challenge is even harder for students with SLDs, because a high percentage self-reported difficulties in taking notes and expressing their ideas using written instead of oral mode, and half of them also reported difficulties in be attentive in class. Similar results were reported also by Olofsson et al. (2012), that interviewing Swedish students with dyslexia confirmed that they have difficulties in taking notes, in dealing with writing and in reading, especially when the text are in a different language (e.g., English). Furthermore, during the qualitative interviews the students with dyslexia revealed that they have identified some useful strategies to compensate their problems, like for example reading summarised or shorter versions of the texts or cooperating with peers (Olofsson et al., 2012). It has been highlighted that the most common strategies to cope with

[28]The values reported here are an average percentage of multiple aspects: organizing essays (SLDs = 76% vs. control = 8%); general organization (SLDs = 67% vs. control = 36%); time keeping (SLDs = 55% vs. control = 31%).

[29] The values reported here are an average percentage of multiple aspects: concentration (SLDs = 52% vs. control = 25%); remembering facts (SLDs = 57% vs. control = 14%); listening (SLDs = 40% vs. control = 12%).

the reading difficulties are identifying the key points within the text, reading the material slowly and out loud, or underling the relevant information and copying them (MacCullagh et al., 2017; Pino & Mortari, 2014). In addition, students with SLDs claimed that incorporating visual and auditory materials, such as pictures, videos, or audio recordings, would enhance their learning experience (MacCullagh et al., 2017; Olofsson et al., 2012; Pino & Mortari, 2014). This finding is coherent with the qualitative investigation implemented by Howard-Gosse et al. (2024) who observed that students with history of reading difficulties uses alternative (non-verbal) study materials more frequently compared to peers with no history of reading difficulties. If they or their lecturers are able to find visual material that is relevant and consistent with the topic, it can represent a valid alternative to compensate the reading difficulties (Howard-Gosse et al., 2024).

Furthermore, there are other relevant issues that these students face and that might require some reasonable adjustment (Riddell & Weedon, 2006). First problem is related to the writing impairments, as it has been observed that students with SLDs struggle more than peers in taking notes and in dealing with written assignments (Mortimore & Crozier, 2006; Olofsson et al., 2012; Pino & Mortari, 2014; Tops et al., 2023). Taking notes is a cognitively demanding task that can be problematic for students with SLDs especially if they have a significant impairment in reading and writing, since they have not automatized these skills (Mortimore & Crozier, 2006; Olofsson et al., 2012; Sumner et al., 2021). This problem can be partially compensated implementing some adjustment like for example proving the students with the PowerPoint presentation before the class, so they can download it and integrate the slides with the information explained (Pino & Mortari, 2014). Other compensatory strategies that have been reported are receiving copies of notes from peers, or recording the lecture (Pino & Mortari, 2014). The final issue, instead, is related to the adjustments made within educational environments. It is imperative to ensure that students with SLDs have access to a quiet setting free from auditory and visual distractions (e.g., peers talking, mobile phones usage, or people moving around) during both lectures and examinations (MacCullagh et al., 2017; Pino & Mortari, 2014). To cope with this issue in class they sit in the rows (MacCullagh et al., 2017) and during the exams they are offered to take the text in a separate room (Pino & Mortari, 2014; Sumner et al., 2021).

2.3.2 How students with SLDs adapt to the new educational context

Both students with and without SLDs experience difficulties adapting to the new learning context; however, this challenge is more pronounced among SLDs (Mortimore & Crozier, 2006). It emerges that the majority of these students self-reported organizational problems which primarily manifested in the management of their study time, the balancing of their academic responsibilities (attending classes, consign assignment on time, etc.) with non-academic appointments. Therefore, this initial adaptation phase can be very challenging especially for those who have not found yet an appropriate study method (Pellegrino et al., 2024; Zamperlin et al., 2024). The literature (Bergey et al., 2015; Chevalier et al., 2017; Kirby et al., 2008) among university students with SLDs reported that these students seem to struggle

more compared to peer with typical development in identifying adequate study strategies. For example, Kirby et al. (2008) observed that university students with history of reading difficulties have hard time in recognizing the main ideas within a text. Furthermore, they are less strategic when preparing for exams, as they report difficulties in processing the information, in understanding how the final assessment will be conducted, and in adapting their study to the exam format (Bergey et al., 2015; Kirby et al., 2008). They struggle in self-monitoring their level understanding of the studied topic, and this encompasses the process of drawing inferences and integrating the new information with their prior knowledge (Bergey et al., 2015). Therefore, it is important to support students providing them support not only through compensatory tools and dispositive measures, but also through informational meetings as well as orientation and tutoring services. It has been observed in literature that taking part to a study method course make the students more strategic both those with typical development (Meneghetti et al., 2016) and those with SLDs (Sini et al., 2025). Facilitating students' identification of effective study strategies is essential to achieving a successful transition (Pellegrino et al., 2024). In addition, this approach enhances academic success, it strengthens students' self-efficacy as well as it positively affects students' attitudes and beliefs towards studying.

It has been observed that emotional, motivational and metacognitive factors can have a positive effect on students' ability to acquire an appropriate study study method (De Beni et al., 2014, 2015; Mega et al., 2014; Meneghetti et al., 2016). Hence, these aspects may be a valuable resource in promoting a successful transition into the university context. Students with SLDs self-report lower level of study motivation (Moè et al., 2019), of study resilience (Casali et al., 2023), of academic self-efficacy (Baird et al., 2009; Casali et al., 2023), and they are less strategic in studying (Kirby et al., 2008). Furthermore, they tend to have lower belief in incremental intelligence (Baird et al., 2009). In other words, they consider their own intelligence as a fixed and immutable trait, that cannot improve nor evolve. This could lead them to make maladaptive effort attributions (Baird et al., 2009; May & Stone, 2010), whereby difficulties in passing the exams are attributed to limited learning and cognitive abilities (fixed and unimprovable) rather than as a result of the level of effort invested in studying. Therefore, it has been demonstrated that design a study method training program, which combines practical workshop with theoretical knowledge about learning and studying, can positively affects students with SLDs (Sini et al., 2025). Multiple Italian university offer to students with SLDs a similar study method support, since it has been observed that it could represent a valid recourse to support students in transiting into university.

2.3.3 Students with SLDs transition to university the role of university

The transition to university can be a challenging moment for students, as their expectations regarding the nature of their studies and the university environment often prove to be incongruent with the actual experience (Hassel & Ridout, 2018; Mortimore & Crozier, 2006; Pino & Mortari, 2014). For students with SLDs can be even more difficult as they usually manifests more emotional and motivational problems compared to peers (Bonuomo et al., 2023; Mugnaini et al., 2009), young adults with SLDs self-reported higher academic anxiety scores,

and more difficulties in relate with peers (Bonuomo et al., 2023). In addition, for these students the adaptation to the new educational context could be harder due to the domain specific difficulties (in reading, writing and /or mathematic). Multiple internal factors can moderate this transition and lead to a positive or negative outcome, likewise there are some external factors that can support and help students. The latter include all the various adjustments that can be implemented by university itself in supporting students with SLDs during in the transition to university. For example, the university may promote the students' acclimatisation to the physical context of the university through the organization of: guided tours of the campus as well as the city; informative and orientation meetings; seminars or informal gatherings where older students and first-year students can meet to exchange ideas and perspectives (Briggs et al., 2012). Secondly, the university should support students when they are choosing the university course they want enrol to. It is important that they have a clear idea of the various careers' paths available (Briggs et al., 2012).

Another aspect is related to the resources as well as the adjustments (compensatory tools and dispensatory measures) available to support these students both in class and during the exams that the university can offer to students with SLDs (Mortimore & Crozier, 2006). Multiple studies in literature have investigated this topic (MacCullagh et al., 2017; Mortimore & Crozier, 2006; Olofsson et al., 2012; Sumner et al., 2021), wondering what adjustments these students need and whether they are reasonable (Riddell & Weedon, 2006). Overall, it emerges that the majority of the request are during the written exams, such as having extra time to execute the test or the opportunity to separate into parts or oral instead of written examination (Mortimore & Crozier, 2006; Olofsson et al., 2012; Sumner et al., 2021). However, there other type of help that can be offered by university like for example individual or group study method training, access to software (e.g., text-to-speech and speech-to-text app or mind-mapping software, etc.) or counselling/psychological services. A recent investigation (Sumner et al., 2021) found that students with dyslexia appreciate and uses the technological tools, whereas they are less willing to engaged into individual or group training that promote the acquisition of appropriate study method. However, it has been demonstrated that supporting students' development of effective study methods and learning strategies can have positive effect on students' academic performance (Sini et al., 2025; Zamperlin et al., 2024; Zeng et al., 2018); these training aim to help students in acquiring adequate study strategies and in becoming autonomous students. In the Italian literature and context, we have different examples that proved the positive consequences of training students' study method abilities (De Beni et al., 2014, 2015; Mega et al., 2014; Meneghetti et al., 2016; Sini et al., 2025). These programs are usually offered to first-year students, with the aim of helping them to improve or acquire study strategies, enhance their self-esteem, and increase their sense of self-efficacy. They are build following the guidelines proposed De Beni et al. (2015) and they are tailored on students with SLDs needs. In parallel, there are international examples (Hillier et al., 2019; Vogel et al., 2007) that proved the efficacy of tutoring or peer-tutoring service, that can represent a valid resource especially for students with SLDs. The tutor helps the students in managing academic assignments and commitments, in studying for exams, and in writing the final exam. This program is usually offered to first-year students, and it has been demonstrated that students with SLDs can be effectively tutored by peers enrolled to a similar degree course and with a

diagnosis of SLDs (Hillier et al., 2019). The tutor-student relationship could be characterized by a greater level of shared experiences and a constructive exchange of strategies and suggestions.

In conclusion the transition from high school to university is an important and delicate moment for all students, and even more so for students SLDs. The positive outcome depends on many individual factors such as students' aspirations and expectations, motivation, emotional experiences as well as external ones like for example the support and assistance provided by university. The combination of these factors produces unique experiences, since students can cope and face challenges and obstacles with their own unique set of tools and resources. Hence, it is important to help these students in adapting to the new and more demanding educational context. Overall, it was observed that students with SLDs that used services offered by university have a better academic perceive them as effective (Tops et al., 2023) and have a better performance (Chevalier et al., 2017; Zeng et al., 2018). More recently, it was reported that students benefit from using university services, as their academic satisfaction and self-efficacy scores positively correlate with the use of compensatory tools and dispensatory measures (Pellegrino et al., 2023). In summary, current research indicates that university support services have a pivotal role in facilitating academic success and achievement among students with SLDs.

2.4 Students with SLDs and learning: the case of science learning

The number of students with SLDs enrolled at university has grown during the last decade (ANVUR, 2022), hence, it is important to explore how they deal with the university environment. We have observed in section 2.2.1 that difficulties in the learning domain (reading, writing and/or mathematic) persist also in adulthood. Consequently, the slowness as well as the inaccuracy could significatively affect academic success.

In the Italian context it has been observed a progressive increase in the percentage of students with SLDs who decide to enrol and graduate in scientific degree course (ANVUR, 2022). The survey, conducted in the academic year 2019/2020, showed the distribution of students with SLDs and with disability into the various disciplinary sectors (see Figure 2.2)

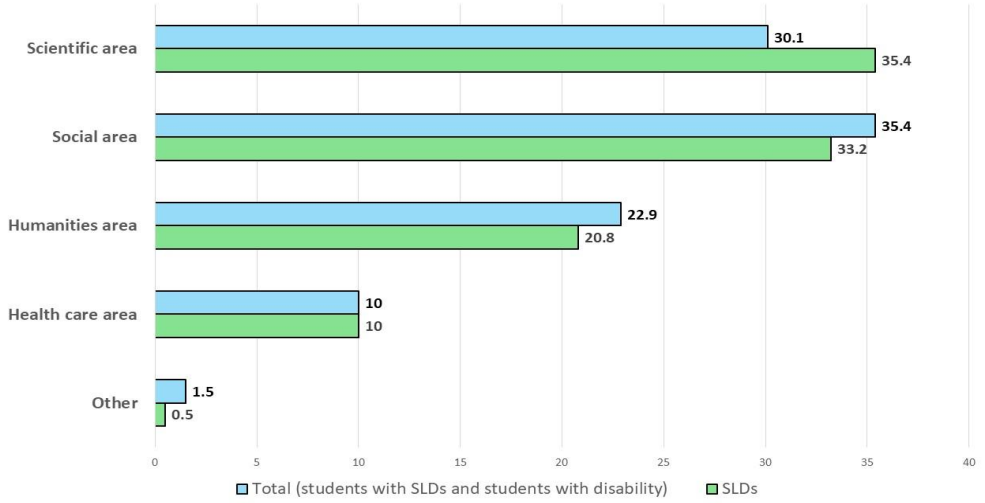


Figure 2.2 Distribution (percentage values) of students with SLDs compared to the whole sample of student with SLDs and students with disabilities, academic year 2019/20 (ANVUR, 2022)

From the comparison, it emerged that 35.4% of first-year student with SLDs (green) chose a degree courses in the scientific, overcoming the percentage of those who selected a degree course in the social area (33.2%) or in the humanities (20.8%). Finally, only 10% opted for a health care course. Furthermore, it pointed out that their distribution slightly differs from the one that can be observed considering together students with SLDs and with disability (light blue).

In the report it has been commented:

"[..] These courses are characterized by the presence of laboratory-based training activities, that require organizational solutions and adequate support to guarantee the participation of students with disabilities or with SLDs, inspired by the principle of "reasonable adaptation", more than what happens in courses in which traditional teaching methods, such as frontal lessons, are dominant." (ANVUR, 2022, page 33)

This preference for the scientific degree courses has been found also in a recent study evaluating the effectiveness of a specific study method training course for first-year university students with SLDs implemented at the University of Turin (Sini et al., 2025). The authors assessed a wide sample of students and the 57.06% of them was enrolled to a science degree course. Since their participation in the training is voluntary, these data provide us with further information: students with SLDs enrolled in a scientific degree program seem to be more willing to use this service compared to those enrolled in other degree programs. This suggests that students' adjustment to the new, highly demanding educational context is more difficult compared to the one faced by students enrolled in social sciences or humanities degree courses. The comprehension of scientific concepts included in these curricula require high level of

abstraction and complexity; furthermore, teaching and learning strategies are unique (Bybee, 2013). The deep-level understanding is achieved not by reading and memorizing textbook information, but it requires the integration of theoretical concepts and real-life context (Brigham et al., 2011; Bybee, 2013).

In recent years, universities have activated and develop services to promote a successful transition to university, some of these opportunities have been tailored on students with SLDs educational needs. However, given the growing number of students with SLDs in science degree courses, these interventions should be more specific and targeted on the peculiarity of these disciplines (ANVUR, 2022). In accordance with the finding of the qualitative investigation carried out by Mortimore and Crozier (2006), revealing that the 64% of the students with dyslexia interview reported that would like to use a subject-specific tutoring support; on the contrary untrained tutoring support service was judged as unnecessary by the 59% of the interview students.

Moreover, the international OECD-PISA report (OECD, 2018) revealed a global drop in students' scientific performance highlighting the need a to develop more effective teaching and learning strategies in these disciplines. The issue is further exacerbated in the Italian context, as national assessments indicate that students' average science score is 20 points below the global mean performance (INVALSI, 2019): Italian average in the scientific domain was 468 compared to the OECD average of 489 points. The more recent assessment (INVALSI, 2022) reported a modest increase to 477 points. However, the overall trend in science performance remains negative. Furthermore, a significant decline was observed among the weakest students (at the 10th and 25th percentiles); hence, the gap between students with the highest and lowest scores widened, on average, by more than 10 points in science (OECD, 2023).

In conclusion, is important to work both in the research and in the clinical-educational fields to identify new strategies and new tools that can support students in learning sciences. In particular, is relevant to invest resources in developing adjustments and strategies that can support students with SLDs during the transition to scientific university degree course. We have summarized the complexity of learning science, especially chemistry, in Chapter 1. We concluded that the more effective way to facilitate and support students is combining chemistry education with the cognitive psychology. This approach can be even more effective when we aim to promote successful learning among students with SLDs. In this case, the intrinsic complexity of the discipline together with the domain specific difficulties (in reading, writing and/or mathematic) and the domain general ones (less efficient EFs, and little WM resources) can negatively affect students' understanding and studying.

2.4.1 The difficulties encountered by adult students with SLDs: an in-depth look at STEM

Students with SLDs have domain specific impairment in automating reading, writing and/or mathematical processes (American Psychiatric Association, 2013). Furthermore, it has

been observed that most of these people share a similar cognitive profile, characterized by significant difficulties in WM and speed processing tasks (Giofrè & Cornoldi, 2015; Pizzigallo et al., 2023; Toffalini et al., 2017). Science education entails the development and application of domain specific competencies, including numerical calculation and mathematical procedures (e.g., solving an exercise), reading comprehension (e.g., interpreting an exercise prompt or a conventional law presented in a textbook), and written communication (e.g., producing a report that summarizes experimental results). Furthermore, to perform successfully also important to have as adequate capacity of maintaining, retrieving and integrating information through WM. However, it has been observed that students with SLDs have more difficulties in WM tasks (Daniel et al., 2022; Kyttälä, 2008; Peng & Fuchs, 2016; Pizzigallo et al., 2023; Toffalini et al., 2017). It was observed that children and adults with SLDs are less efficiency tasks that require to manipulate ana handle verbal, phonological information (Daniel et al., 2022; Liebel & Nelson, 2017); some investigation that focuses the attention on students with SLDs with a significant impairment in mathematics, showed that they also struggle in dealing with complex visuospatial material (Mammarella et al., 2018; Peng et al., 2016). Both domain specific and domain general issues remain in adulthood (see, Reis et al., 2020), their performance in reading, writing, and/or mathematics may improve through educational and clinical interventions, but they will not to reach the level of students with typical development. These weaknesses can interfere with their ability to organize, remember, retrieve and use the information acquired (Flynn, 2014; Lytra & Drigas, 2021; Scruggs et al., 2013; Swanson & Sáez, 2003) and have a negative effects in terms academic performance. Furthermore, specific difficulties in automating learning processes (reading, writing and/or calculation) can affect the information acquisition phase as well as the students' performance during the exam, because they could limit their explanation ability, especially in written form, and they could compromise the correct execution of the assigned exercise (Scruggs & Mastropieri, 1993).

Nevertheless, it has been demonstrated that students with SLDs if they are provided with adequate accommodations can achieve a performance comparable to peer with typical development (Demirdag, 2014; Villanueva et al., 2012; Wei et al., 2013). However, it has been reported that these are still rare in many science educational context (see for example, Dunn et al., 2012; Scruggs et al., 2013; Thurston et al., 2017). It has been reported that teachers are often not adequately prepared and trained to deal with SLDs, so they do not have knowledge about SLDs and strategies that can be implemented, and they do not know how these students function (Scruggs et al., 2013). A recent investigation that involved Italian teachers from primary (1st to 5th grade) and secondary school (6th to 8th grade) revealed that the latter self-reported to have lower knowledge compared to primary school teacher (Re et al., 2021). A negative teacher attitude can affect the performance and motivation of these students (Sironi et al., 2019). In fact, inadequate training can negatively influence the way teacher perceives the student and could generate the projection of low expectations on the student (Carlisle & Chang, 1996) and these could negatively undermine self-esteem and academic self-efficacy (Carlisle & Chang, 1996; Grolnick & Ryan, 1990; Montgomery, 1994) as well as their attitude to share their difficulties and ask for the needed adjustments (Grimes et al., 2019; Haft et al., 2023; Mamboleo, Dong, Anderson, et al., 2020).

In conclusion, given the current situation it is important to reflect and keep in mind the specific difficulties of university students with SLDs in scientific disciplines. A starting point could be to investigate the lectures' knowledge about SLDs and Special Needs Education and important, and to provide them with useful information that can help them in implementing an inclusive learning environment. At the same time, it is necessary to support students developing specific learning strategies and helping them to enhance their metacognitive skills, that represent an excellent resource for academic success and to compensate for one's difficulties automatization (Mega et al., 2014; Trainin & Swanson, 2005).

2.4.2 An overview of the intervention programs targeting students with atypical development

The need to implement inclusive teaching in order to limit the risk of school and university drop out and to promote equal opportunities for all students is one of the goal included in the 2030 Agenda for Sustainable Development (ONU, 2015). For this reason, it is essential to develop new technologies and compensatory tools that ensure equal learning opportunities for all students, including in the university environment. A systematic literature review (Kolne & Lindsay, 2020) revealed that the first studies in this sense were carried out twenty years ago, and in many case the investigation involved students in the final years of secondary school. These experimental programs or training have been designed on late-adolescent in order to limit school dropout, but some of them have as additional goal to promote academic success and interest scientific disciplines (Kolne & Lindsay, 2020) The included studies respected the guidelines of the American Neurobiological Association (Getchius et al., 2010) and were evaluated by two independent judges, according to the quality evaluation standards criteria indicated by Kmet et al. (2004). All the studies were conducted in the United States, have recruited late-high school or university students (Burgstahler & Chang, 2007, 2014; Burgstahler & Cronheim, 2001; Burgstahler & Doyle, 2005; Izzo et al., 2011; Kim-Rupnow & Burgstahler, 2004; Street et al., 2012); while other studies targeted the intervention on secondary school students (Gregg et al., 2017; Lam et al., 2008; Lemaire et al., 2002). The authors identified 17 studies that respected the inclusion criteria and 10 of these involved also students with learning difficulties or special educational need (only few of them gave us some interesting results on student with SLDs). Overall, the literature review revealed different support activities whose efficacy was tested, such as:

- Tutoring services or study groups (in person or online/remotely) leaded by peers or experts (Burgstahler & Chang, 2007, 2014; Burgstahler & Cronheim, 2001; Burgstahler & Doyle, 2005; Gregg et al., 2017; Kim-Rupnow & Burgstahler, 2004; Street et al., 2012).
- Guidance services and/or summer internships (Burgstahler & Chang, 2007; Burgstahler & Cronheim, 2001; Burgstahler & Doyle, 2005; Izzo et al., 2011; Lemaire et al., 2002).
- Courses to promote the acquisition of specific and transversal skills, in particular self-advocacy (Gregg et al., 2017; Izzo et al., 2011; Kim-Rupnow & Burgstahler, 2004; Lam et al., 2008).

The different studies aimed to promote students' motivation and/or likelihood to pursue scientific career path. Only two studies, Lam et al. (2008) and Gregg et al. (2017), included in their investigations students with SLDs, but the results are limited since both investigations targeted an heterogenous sample of students with atypical development. In the first one (Lam et al., 2008), the authors tested the effectiveness of a program based on an investigative approach. The conclusions drawn from this study are extremely limited in scope. The intervention was targeted at a select group of eleven students in grades six, seven and eight who had been assigned an Individualized Education Plan (IEP). However, only four of these students had a documented diagnosis of Specific Learning Difficulties (SLDs). Furthermore, the control group were fifteen peers with typical development. The training was designed to promote the acquisition of theoretical concepts related to the engineering world (areas of study: mechanics, construction and aerodynamics). The intervention was structured in two moments: an intensive course in the summer and a series of monthly seminars (to consolidate the topics) the following year. At the end of the program, the findings revealed a positive change in self-perceived idea of themselves as students and a greater interest in pursuing an engineering career in the future, but the effect was significant among students with typical development. Furthermore, students' knowledge was measured with a 15-item multiple-choice test administered before and at the end of the summer workshop. The authors reported a significant improvement in students' performance at the post-test: the descriptive analyses showed a greater improvement emerged for the students with IEP, although the difference between the groups was not significant, probably due to the low number of participants. The present investigation considered the students with SLDs together with other neurodevelopmental disorders; hence, it is difficult to generalize the conclusion. However, it represents one of the first attempts to explore the effectiveness of interventions aimed at improving motivation and learning in scientific disciplines among students with SLDs.

Another interesting study is the one carried out by Gregg et al. (2017), whose goal was to test the effectiveness of virtual mentoring program designed to reduce dropout among students with atypical development in science education. The study involved 189 middle and high school students with atypical development, such as SLDs (41%), ADHD (22%), autism spectrum disorder (9%) or other difficulties (28%). Students participated in a four-year virtual-mentoring program including multiple sessions. These could be through digital voice communication (e.g., audio, phone or video calls) and through written communication (e.g., email, messages, chat or social media posts). The intervention efficacy was assessed with a pre and post online survey, measuring the differences in students': aspiration (students' inclination to persist in studying science and pursuing a scientific career); self-determination (individuals' capacity to act as the principal agent of their own); self-advocacy (people ability to effectively communicate, convey, negotiate, or assert ones' interests, desire, needs, etc.); math and science self-efficacy (students' perception of their competence in math and in science). Overall, the analyses pointed out positive outcomes in self-determination and self-advocacy. However, the analyses on the students with SLDs showed a significant decrease in the students' aspirations, self-efficacy and interest in both math and science. These results lead to a very interesting conclusion: the implementation of supportive programs promoting the development of soft skills, are not sufficient to stimulate interest and the perception of competence. This finding was in

accordance with those reported in the qualitative investigation carried by Mortimore and Crozier (2006), concluding that students with dyslexia prefer subject-specific tutoring support over general tutoring support.

However, these are other examples in the literature, that were not included in the systematic literature review implemented by Kolne & Lindsay (2020), that aimed to explore the topic of learning difficulties and science education. There is a set of recent research carried out in the US context on high school students (Freeman et al., 2023; Gottfried & Sublett, 2018; Plasman & Gottfried, 2018). Again, the investigations targeted heterogenous groups of students with atypical development. This group of studies investigated the students' likelihood to include applied scientific courses[30] in their curricula and whether this affects their future choice of university career. Overall, it emerged that: students with atypical development are less likely compare to students with typical development to enrol in applied scientific courses (Gottfried & Sublett, 2018). Moreover, even when they do it, this does not appear to positively affect their future decision to attend advanced mathematics or science courses (Gottfried & Sublett, 2018). However, it has been demonstrated that taking part to applied scientific course decrease dropout among students with atypical development, and it increases the likelihood that they will pursue university studies (Plasman & Gottfried, 2018). In addition, a more recent investigation concluded that students with atypical development that attended more the applied scientific courses during high school are more willing to enrol in a scientific university degree course (Freeman et al., 2023). Traditional science education relies on verbal explanation, and it results in simply memorizing text-book instruction, a learning approach that could be particularly hard for students with impairments in reading (Scruggs et al., 2013). Therefore, the implementation of applied courses aims to promote math and scientific concepts and skills in a more relevant and meaningful way (Freeman et al., 2023).

Finally, focusing the attention on university students there are studies (Graves et al., 2011; Kreider et al., 2018) that investigated the effectiveness of implementing support strategies to promote academic success in students enrolled in scientific courses. Their peculiarity is that both targeted students with SLDs. The study carried out by Graves et al. (2011) studied the advantages of providing students with video-recorded class and giving them the asynchronous online access to course material. It was a qualitative investigation on a small sample of university students with SLDs, but it revealed interesting findings. Students claimed that possibility to remotely access to course material and recorded class facilitated their learning and studying. They had the opportunity to revise notes and to clarify inconsistencies, and they could pause the registration listen to it aging when they got distracted. In other words, this tool allowed them to self-accommodate and to cope with their learning impairment (Graves et al., 2011). On the other hand, Kreider et al. (2018) studied the effect of a 4-semester multi-method intervention designed to support students with SLDs. The authors investigated the efficacy of a program integrating interventions that promote changes at institutional, personal, and interpersonal levels. At the institutional level, initiatives focus on making people aware of the

[30] Applied scientific courses are educational programmes that emphasize the application of math and science concepts to real-world problems rather than through abstract definition (Plasman & Gottfried, 2018)

strengths and weaknesses of students with SLDs in the university context (e.g., establishing a specific university commission safeguarding students with SLDs and attempting to integrate it with the institutional reality). In parallel, interventions addressing students' personal and interpersonal development were implemented (e.g., meeting and training groups on SLDs and on personal growth, developing a career/professional development centre). The results of this experience were positive and higher levels of self-efficacy, self-advocacy, and personal development were observed in students with SLDs; furthermore, these students self-reported a greater sense of belonging to the university reality.

In conclusion, this brief review of the existing literature clarifies that there are valuable tools that can be implemented in younger students to promote their interest and their self-efficacy in scientific disciplines. It emerged that literature on scientific university education among students with SLDs is still scares. However, the promising results reported Kreider et al. (2018) validated the effectiveness of an integrated and multi-modal approach that integrating institutional, personal and interpersonal level can successfully support students with SLDs in transit to university. However, it did not provide practical example of tools ore strategies that can supports students in understanding abstract scientific concepts.

2.4.3 Study method and compensatory tools to help students with SLDs in scientific disciplines

It has been illustrated (see section 2.2) that students with SLDs have to cope with domain general impairments (e.g., WM, EFs, speed processing, etc.) as well as with domain specific issues (in reading, writing and/or math). This last section is dedicated to the presentation of some examples of compensatory tools that can be introduced to support these students' learning experience when they have to deal with scientific courses at university level.

It has been observed that difficulties in automating reading, writing and/or calculation remains in adulthood. Therefore, these students might take more time to read of the material, and, in some cases, they could have an insufficient understanding. It has been demonstrated (Israel et al., 2013) that providing students with a brief general introduction of the topic and the order in which it will be presented could be useful for students with learning difficulties, as it activates listening and promotes knowledge recovery. Similarly, a recap at the end of the class can help students in organizing the heard information, and in integrating the new knowledge with those stored in long-term memory (Israel et al., 2013). Another valuable strategy is to explain a concept using multiple channel, for example providing auditory (verbal) as well as pictures/video (visual) illustrations, guiding students in the understanding of the image (Israel et al., 2013). Diagrams, tables or a pictures, should be supported by oral explanation, so students can then use this visual tool effectively (Israel et al., 2013). Furthermore, this presentation should be divided into smaller units, offering students with a manageable amount of simultaneous information that they are able to process depending on their limited WM resources (Pizzigallo et al., 2023). The use of images has been widely shown to be effective both in enhancing comprehension and in serving as a mnemonic aid to support retrieval in individuals

with SLDs (see for example, Brigham, 1992; Mastropieri et al., 1985). Other useful examples are the software that can support students in reading (text-to-speech) as well as in writing (speech-to-text or video/audio recording). In scientific disciplines, it has been demonstrated how technological tools can guarantee an interactive learning experience (Marino et al., 2010), offering opportunities to experiment the application of theoretical laws to concrete reality through virtual laboratory or designing virtual and dynamic representation/simulations of scientific phenomena that cannot be directly observable. The studies available in literature are only in students with typical development, but it is possible that they could represent a valuable tool for students with SLDs (Brigham et al., 2011).

Furthermore, it has been demonstrated that, even in scientific disciplines, the use of some verbal mnemonic strategies, such as the use of keywords, could be extremely effective (Mastropieri et al., 2005; Mastropieri & Scruggs, 2010; Scruggs et al., 1985). However, it has been observed that mnemonic strategies relying on visuo-spatial channel are more effective for students with SLDs (Brigham, 1992; Mastropieri et al., 1985), as they load on visuospatial WM resources that are a valuable strength especially among students with reading and writing impairments (Giofrè & Cornoldi, 2015; Toffalini et al., 2017). In fact, it has been demonstrated presenting scientific concepts using the visual-spatial channel (graphs, pictures, videos, etc.) is particularly advantageous for students with SLDs (Bergerud et al., 1988; Bulgren et al., 2002; T. Lovitt et al., 1986; T. C. Lovitt & Horton, 1994) and positively influences students' performance (Scruggs et al., 2010).

Finally, it has been observed that another way to support study skills is to work to enhance the students' individual soft skills such as self-efficacy and self-advocacy (Pfeifer et al., 2020) and at a metacognitive competence (Trainin & Swanson, 2005). Evidence indicates that, among university students with SLDs, adopting a metacognitive approach to learning and studying leads to multiple benefits and fosters academic success at levels significantly higher than those observed in students with typical development (Trainin & Swanson, 2005). Guiding and supporting these students to a conscious use of compensatory tools and strategies, structuring training courses that favour the acquisition of greater awareness of their own resources and fragilities is functional to promote their academic success (Sini et al., 2025) and well-being (Kreider et al., 2018).

2.5 Concluding remarks

The gradual increase in students with SLDs enrolling in science degree courses necessarily requires a comprehensive examination of the specific challenges they face in these disciplines. In recent years, there has been an increase in international interest in this field, but there is still a need to explore the more concrete aspects. More precisely, there is the need to identify the compensatory tools or strategies that can be implemented at university level to promote and facilitate learning.

The aim of this chapter is to provide a framework for this reflection, starting from the analysis of the unique features of these disciplines and of adults with SLDs. A brief analysis of the existing literature suggests that it is possible to promote the academic success of university students with SLDs in scientific disciplines, by adopting some measures.

For instance, it has been demonstrated that the implementation of multimodal communication is a crucial factor in the creation of more accessible explanations. In other words, this consist of presenting the same topic using both verbal-auditory and visual-spatial. The latter can represent an important resource, especially for students with SLDs who manifest fragility in reading and writing. This is due to the fact that visual-spatial skills are frequently a strength for these students. Moreover, research has demonstrated that the retrieval of information through the utilisation of visual-spatial strategies is more effective in students with SLDs. It is therefore vital to promote, implement and study the effectiveness of teaching mnemonic strategies that exploit these different channels.

In conclusion, it is imperative to initiate and carry out intervention projects that operate concurrently on multiple fronts. Interventions are required at two levels: firstly, the training of teaching staff must be broadened; secondly, effective strategies and tools must be disseminated to individual students. These strategies and tools must be made easily accessible to students with and without SLDs in their everyday university life.

Chapter 3: Investigating the relationship between working memory and chemistry learning in undergraduates with typically development and with Specific Learning Disabilities (SLDs)

3.1 Study 1: Preparatory investigation testing the adequacy of chemistry learning task among undergraduates with typical development

The present preparatory study was built with a double purpose: firstly, to investigate the adequacy of a chemistry learning task designed specifically for the undergraduate students; and secondly, to explore the relationship between the performance in this task and in different cognitive tasks.

Methods

Procedure

The study protocol is part of a wider research project "Exploratory investigation of the cognitive processes involved in learning chemistry" aimed at understanding which cognitive processes are engaged in chemistry learning in undergraduates with typical development and with SLDs. The project was submitted to the Bioethical Board of the University of Turin for approval, and it was accepted (protocol nr. 0059554, date 30/01/2023). The established design consists of two sessions, which were administered separately: one for the assessment of chemistry learning ability and an additional session for the assessment of the domain-general cognitive abilities. The collection of the data was implemented between February and June 2023. These two phases were structured as follows:

- *Assessment of chemistry learning abilities*
  It lasted approximately one hour, and it was carried out during a collective session. Students were asked to perform a chemistry task (described below), and to fulfil a short questionnaire asking them few personal details (age, gender, and type of degree course).

- *Assessment of domain-general cognitive abilities:*
  This second phase lasted approximately two hours, and it was carried out during a collective session. Students were assessed with two verbal and two visuospatial WM tasks. Additionally, they were asked to fulfil a questionnaire concerning students' cognitive stiles (all these tasks are deeply described below).

Participants

The chemistry learning assessment involved 39 first-year undergraduate students (28 male and 11 female, M_{age} = 20.6 years, SD_{age} = 2.29 years) enrolled in a scientific-related bachelor's degree course at the Polytechnic University of Turin (N = 25, 64.10%) and at the University of Palermo (N = 14, 25.90%). But only 20 of them (51.28%) proceeded to the second phase of the assessment, which encompassed the domain-general cognitive abilities. This sub-sample included 15 male (75%) and 5 female (25%) and the mean average age was 20.6 years (*SD* = 2.79 years).

All the participants attended at least a single chemistry course during the first semester (September 2022-January 2023) and voluntarily participated to the research without receiving any monetary compensation.

Instruments

Chemistry Task (CT)

The CT was designed specifically for the present research, and it was structured in accordance with the Learning Task included in the Italian battery for the assessment of study method among undergraduates - AMOS test (De Beni et al., 2014). Although, the general structure of the aforementioned task was preserved. A slight modification was implemented to more accurately reflect the students' daily university lecture experience. The CT was organized as follows: students listened to a 23-minute video-classes (instead of reading a written text – see De Beni et al., 2014); they studied and reviewed autonomously the concepts explained in the video-class for 10 minutes, during which they could use their own notes and the slides (the same used in the video-class). Finally, a 10-minute break, they were asked to perform a final test. The CT was created thanks to the collaboration of a multidisciplinary team that included chemistry and psychology professors.

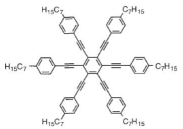
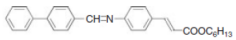
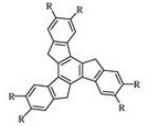
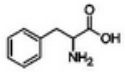
The video-class was recorded, and it lasted 23 minutes during which a chemistry professor (Prof. Lombardo Renato, Department of Biological Chemical and Pharmaceutical Sciences and Technologies, University of Palermo, Italy) explained the liquid crystals, providing historical information and knowledge about their structural arrangement and their technological applications (e.g. liquid crystal displays). The decision to implement a recorded video-class rather than a written text had two reasons: reproducing an ecological learning situation, what they experience in the CT was quite similar to what they experience in their everyday academic life; secondly, allowing us to be provided with a replicable assessment tool. Finally, the topic of the video-class (liquid crystals) was chosen because it was not included in any general chemistry course, and it would exclude any previous-exposure effect. Furthermore, liquid

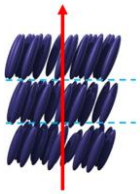
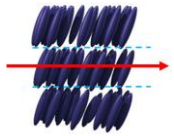
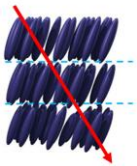
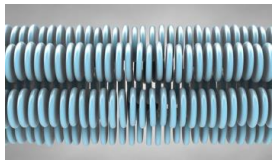
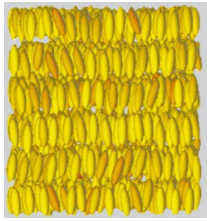
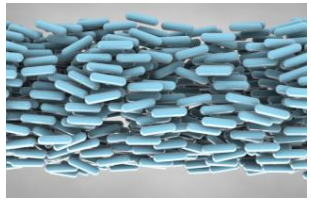
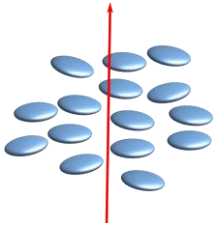
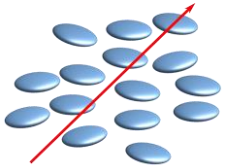
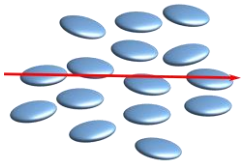
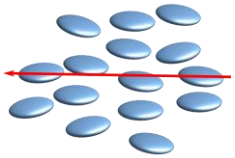
crystals are easily explainable and do not require any prior specific conceptual knowledge in chemistry. Moreover, their relevance to everyday life is pronounced, given their multiple technological applications. Lastly, the understanding of this topic relies on students' ability to integrate and interconnect sub-microscopic and macroscopic level of reality.

After the video-class, students were assigned with a 10-minute study period, and subsequently they were asked to complete the final test. This test was a multi-choice task consisting of ten questions (four alternatives each) assessing whether the students had acquired the chemistry knowledge and concepts presented in the video-class. The test was administered online using Google Form. The ten questions were divided as it follows: five were textual (questions and the answers were written text), and five were visual (questions were in words and the four alternatives were pictures). The final chemistry test is reported in Table 3.1.1.

Table 3.1.1 Textual and visual questions included in the chemistry task (CT). Given that the task had been originally assessed in Italian, an English translation was provided. The correct answers are reported in bold

Number of questions	Question	Alternatives
Q1	Quando è stato coniato il temine cristallo liquido? [When was the term 'liquid crystal' first used?]	a. Fine '700 [At the end of 18th century] b. Anni 50 del '900 [1950s] ***c. Fine '800 [At the end of 19th century]*** d. Anni 90 del '900 [1990s]
Q2	La formazione di un cristallo liquido può essere determinata da: [The formation of liquid crystals can be determined by:]	a. Una variazione di densità [A density change] ***b. Una variazione di temperatura [A temperature change]*** c. Una interazione con la luce [An interaction with light] d. Tutte le precedenti [All the above-mentioned alternatives]
Q3	Nella fase nematica i mesogeni [In the nematic phase, mesogens:]	***a. Sono disposti secondo una direzione preferenziale [Are placed according to a preferential direction]*** b. Presentano un ordine posizionale [They show a positional order] c. Si distribuiscono in piani sovrapposti [They are organised in overlapping layers] ***d.*** Occupano posizioni fisse [They have fixed positions]
Q4	Nella fase smettica C: [In smettic C phase:]	a. Non esiste un direttore preferenziale [There is no preferential director] b. Il direttore e la normale del piano coincidono [The director and the normal to the plane coincide] c. Il direttore e la normale del piano hanno direzioni opposte [The director and the normal to the plane have opposite directions] d. ***Il direttore forma un angolo con la normale del piano [The director forms an angle with the normal to the plane]***

Q5	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:]	***a. La fase chirale non è presente e il pixel risulta spento [The chiral phase is not present, and the pixel is switched off]*** b. La fase chirale è presente e il pixel risulta acceso [The chiral phase is present, and the pixel is switched on] c. La fase chirale è presente e il pixel risulta spento [The chiral phase is present, and the pixel is switched off] ***d.*** La fase chirale non è presente e il pixel risulta acceso [The chiral phase is not present, and the pixel is switched on]			
Q6	Quale delle seguenti immagini non corrisponde ad un sistema chirale? [Which of the following picture does not correspond to a chiral system?]	A	B	***C***	D
Q7	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?]	A	***B***	C	D
					
Q8		A	***B***	C	D

	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?]				
Q9	Quale delle figure sottostanti corrisponde ad una fase nematica? [Which of the following pictures correspond to a nematic phase?]	A	B	C	***D***
					
Q10	Quale è il corretto direttore per una fase nematica discotica? [Which picture properly identifies the director in the discotic nematic phase?]	***A***	B	C	D
					

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). The original set of 15 queries, as well as the pictures that illustrate the selection procedure are reported in Appendix 1 (p. 172). We defined factual questions as those in which the proper answer mainly relies on the recall of information; whereas conceptual questions were 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 3.1.2.

Table 3.1.2. Classification of the ten questions of the CT based on the type of knowledge (factual or conceptual) and the cognitive processes involved (decoding, recall of lecture information, inference)

	Factual	Conceptual	Decoding	Recall of lecture information	Inference
Q1	X		X	X	
Q2		X	X	X	
Q3		X	X	X	
Q4	X		X	X	X
Q5		X	X	X	X
Q6		X	X	X	
Q7	X		X	X	
Q8	X		X	X	X
Q9		X	X	X	X
Q10		X	X	X	

Note. Q1-Q5 are the textual questions; Q6-Q10 are the visual questions.

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

factual (maximum score = 4) and conceptual (maximum score = 6) questions was calculated too, and their score was transformed into percentage so the two measures could be compared.

Verbal Working Memory (WM) tasks

Verbal WM was assessed with two different tasks: the Word Span task – WS (Spinnler & Tognoni, 1987) and the Listening Span Task – LST (De Beni et al., 2008). Both tasks were adapted to the collective administration. The two tasks both burden the phonological WM component but the first requires the maintenance of verbal information, whereas the second needs the maintenance and the manipulation of verbal information.

The WS (Spinnler & Tognoni, 1987) task asked the students to listen to lists of words and the length of these lists gradually increased. Students were asked to recall for each list all the words in the propter order of presentation. The task consisted of eight levels, two lists each; it started with level 2 (two words for each list) and it stopped at level 9 (nine words for each list). The words were all disyllabic and familiar (e.g., "car-ta" [pa-per], "di-to" [fin-ger], "don-na" [wo-man]). The final score (maximum score = 88) in this task was obtained summing up the number of correct words recalled (in the proper order) for each list.

The LST (De Beni et al., 2008) consisted of listening to a set of sentences (the number of sentences gradually increased in accordance with the degree of difficulty). For each statement students were asked to evaluate the truthfulness (whether the phrase is true or false) and at the end of the set they had to recall (according to the order of presentation) the last word of each sentence. This task was structured in six levels from level 2, two statements, up to level 6, six statements. For example, students listened to the following sentences: "Human beings could survive even without *oxygen*" (False), "Soccer is a sport that is played exclusively in the high *mountains*" (False), and "It is possible to die if you are bitten by a *viper*" (True). Afterwards, they should recall the words "oxygen", "mountain", and "viper", in this exact order. The total score (maximum score = 20) in this task was the sum of the words that students properly recall. According to the manual (De Beni et al., 2008) the split-half correlation is $r = .87$.

Visuospatial Working Memory (WM) tasks

Visuospatial WM was assessed with two different tasks: the Matrix Span – MS (De Beni et al., 2008) and the Imaginative Puzzle – IP (De Beni et al., 2008; Richardson & Vecchi, 2002). The two tasks were adapted to the collective administration, and they both relied on visuospatial WM resources. The MS concerns the maintenance of visual information, whereas the IP asks the students the maintenance and the manipulation of visual information.

The MS was a visual span task, requiring students to observe a matrix consisting of grey and white cells for a limited period of time. After that, they had to indicate on the same empty matrix the coloured cells. The observation time increases along with the degree of difficulty (from level 1 the easiest up to level 11). For example: level 1 (one out of four grey cells) the time was 2 seconds; level 2 (two out of four grey cells) the time was 3 seconds; level 11 (eleven out of twenty-two cultured cells) the time was 12 seconds. Each level consisted of three trials,

and it was succeeded if students correctly recalled all the cells in at least two of them. The total score was obtained summing up the level-related number of the three most complex matrices completed correctly. For example, if students managed to complete level 11 and they do correctly all three tasks, the final score is 33 (11+11+11), but if they failed one task out of three, the total score is 32 (11+11+10) because we counted the two correct answer of level 11 and the third most complex matrix, they completed accurately that belong to level 10. Whereas if they for example answered correctly at least two out of three tasks in level 9, but then they fail two out of three tasks in level 10, the total score will be 28 (9+9+10). The maximum score in the present task was 33. According to the manual (De Beni et al., 2008) the Cronbach alfa is α = .84.

The IP task was organised in nine levels (form 2 up to 10) and each level was made of three tasks. Students observed a familiar object (e.g., a luggage, a telephone, a baby carriage, etc…) for 2 seconds, after that the same item was presented shattered into multiple enumerated pieces, with the number of fragments corresponding to the level of difficulty (e.g., level 2 = two pieces, level 3 = three pieces, etc…). Therefore, students had to mentally reassemble these fragments and to position them in the proper order with a given matrix, in a limited period of time. The time increased within the degree of difficulties from level two (10 seconds) up to level 10 (90 seconds). Students succeeded at the level if they completed at least two out of three tasks per level. The final score was the sum of the level-related number of the three most difficult puzzles correctly reorganized. For example, if students managed to reach level 10 and they do correctly all three tasks, the final score was 30 (10+10+10), but if they failed one task out of three, the total score was 29 (10+10+9); whereas if they succeeded level 8 (at least two out of three tasks), but then they failed two tasks out of three tasks in level 9, the total score would be 25 (8+8+9). The maximum score in this task was 30. According to the manual (De Beni et al., 2008) the Cronbach alfa is α = .83.

Cognitive Style Questionnaire (CSQ)

The goal of the present questionnaire is to gather if the student is more a visual rather than a verbal person and vice versa. The CSQ (De Beni et al., 2014) is a self-report questionnaire consisting of nine statements. Students were asked to indicate the degree of accordance/the frequency of a specific behaviour on a 5-point Likert's scale (from 1 "totally disagree/never" to 5 "totally agree/always"). Here some examples of these statements: *"Mi riescono bene i giochi con le parole (anagrammi, sciarada, inventare parole)"* [I do well with word games (anagrams, charades, inventing new words)]; "*Mi resta più in mente la parte scritta dei libri di testo che non i grafici*" [I remember the written part of books more than the graphics]. The total score was the average point on Likert's scale for the nine statements. It should be noted that some of them were reverse items. In this case the score must be transformed as follows: 1 when students indicated 5, 2 when they indicated 4, and so on. Finally, the total raw score must be standardized in a z-score (M= 0 and SD = 1) by using the mean and the standard deviation reported in the manual (De Beni et al., 2014). The detailed interpretation is reported in the manual, but in general a z-score < - 0.50 indicates a predominantly visuospatial cognitive style, whereas a z-score > 0.50 a predominantly verbal one. The test-retest reliability is r = .77 (De Beni et al., 2014).

Data Analysis

The main purpose of the study was investigating the adequacy of the procedure implemented. First, we reported a qualitative analysis of the Chemistry Task (CT), that was designed hoc for the investigation, since there was no standardized Italian instrument able to assess undergraduate students' chemistry learning ability. We computed means and standard deviation of the CT for the whole sample (39 students) and we reported a qualitative analysis which proves that the task is well-structured in terms of degree of difficulty. Finally, we reported the preliminary results of the correlational analysis between the performance at the CT and the cognitive abilities. This was computed on the sub-sample of students that participated to both parts of the study (N = 20),

Results

Qualitative analysis of the Chemistry Task (CT)

First, we calculated the means and the standard deviations of the students' performance in the CT, both total scores and partial scores (textual and visual questions) were examined (see Table 3.1.3).

Table 3.1.3 Mean (M),standard deviation (SD) and median for the accuracy (number of correct answers) in the total score and the partial scores (textual and visual) of the CT

	Correct answers				
	M	*SD*	*Median*	Skewness	Kurtosis
Total score	5.41	2.11	6	.24	-.70
Textual score	3.15	1.20	3	-.02	-.95
Visual score	2.26	1.29	2	.34	-.58

Then, we further investigated students' performance in each question: the percentage of accuracy of the 10 questions was measured, and we examined how students' performance was distributed throughout the four alternatives. These results are reported in Table 3.1.4.

Table 3.1.4 In depth investigation of the students' performance for each question of the CT

		Correct answer	Percentage of accuracy	Alternative				Missing
				A	B	C	D	
Textual	Q1	C	61.6%	5.1%	28.2%	**61.6%**	5.1%	0
	Q2	B	76.9%	5.1%	**76.9%**	7.7%	7.7%	2.6%
	Q3	A	53.8%	**53.8%**	20.5%	23.1%	2.6%	0
	Q4	D	84.7%	5.1%	5.1%	5.1%	**84.7%**	0
	Q5	A	38.5%	**38.5%**	28.2%	20.5%	10.2%	2.6%
Visual	Q6	C	33.4%	17.9%	25.6%	**33.4%**	20.5%	2.6%
	Q7	B	43.6%	35.9%	**43.6%**	10.2%	7.7%	2.6%
	Q8	B	69.2%	25.7%	**69.2%**	5.1%	0	0
	Q9	D	30.8%	17.9%	12.8%	35.9%	**30.8**%	2.6%
	Q10	A	48.7%	**48.7%**	17.9%	12.8%	10.3%	10.3%

These findings demonstrated that questions have different degrees of difficulty, and no floor (accuracy = 0 %) or ceiling (accuracy = 100 %) effects were observed. Overall, students' accuracy (total score, Table 3.1.3) averaged 50%, but examining the single questions, it can be noted that: some queries were easier (higher percentage of accuracy) than others such as Q2, Q4 and Q8; some ones were harder (lower percentage of accuracy) than others such as Q5, Q6 and Q9. Finally, it can be noted that the accuracy in the textual questions (Q1 - Q5) was higher compared to the performance observed in the visual ones (Q6 - Q10), suggesting that students answered worse when the question had pictures as alternative responses.

Correlational analysis between Chemistry Tsk (CT) and cognitive tasks: preliminary results

The correlational analysis was computed on the sub-sample (N = 20) of students who took part in the cognitive assessment too. Due to the limited sample-size, these findings were hardly conclusive, but the decision to include them in the present section had two reasons: first, we obtained significant correlations, and this was surprisingly due to the sample-size; second, the results were crucial in understanding they were more correlated to the CT performance than others (see Table 3.1.5). Since the skewness and the kurtosis (Table 3.1.3) show a non-normal distribution, we computed a non-parametric correlation analysis using Speraman rho's.

Table 3.1.5 Mean (M) and standard deviation (SD) of cognitive tasks and CT performance (total score), and correlational analysis between them (N= 20)

	M (SD)	1	2	3	4	5
1. WS	60.26 (7.82)	1				
2. LST	14.37 (3.00)	.33	1			
3.MS	30.63 (2.57)	.53*	.23	1		
4. IP	23.58 (5.26)	.00	.10	-.31	1	
5. CT (Total score)	6.40 (2.01)	.43	.46*	.23	.46*	1

Note. * p< .05; ** p< .001.

Note. WS = Word Span; LST = Listening Span Test; MS = Matrix Span; IP = Imaginative Puzzle; CT = Chemistry Task.

The correlational analysis showed a medium positive significant correlation between the CT total score and two WM tasks: LST (Verbal WM) and IP (Visuospatial WM). Finally, a medium positive and significant correlation was found between the verbal (WS) and the visuospatial (MS) span tasks.

Finally, we computed an additional correlational analysis between the two partial CT scores (textual and visual) and the students' score at the Cognitive Style Questionnaire (CSQ). The correlations were not significant, but we observed a medium positive correlation (rho = .32) between CSQ and CT's verbal score, and a medium negative correlation (rho = -.37) between CSQ and CT's visual score.

Discussion

The present preparatory investigation was implemented to test and to prove the adequacy of an experimental protocol aimed at grasping the relationship between cognitive processes and chemistry learning. In particular, it represented an initial attempt that explores the relation between undergraduate students' WM abilities and their performance in a chemistry learning task. Due to the lack of standardized instruments that measure students' chemistry understanding we designed a specific task that was administered to a small sample (N= 39) of Italian undergraduate students. Moreover, we were able to explore the relations between students' performance and their WM abilities on a smaller sub-sample (N =20), that included the few students that voluntarily took part in the further assessment phase.

The qualitative analysis of the CT illustrated that the ten questions present different degrees of difficulties, and no floor or ceiling effects were observed. The findings showed that some questions were easier than others. The easiest ones mainly asked students to recall information explained in the video-class or were questions that were highly related to students' vectorial geometry knowledge. Whereas the most difficult ones required the recollection of information,

as well as a deep level understanding of the topic. These finding are in accordance with Crone at al. (2006) who concluded that the tasks that require maintenance and manipulation of information (verbal or visuospatial) are cognitively more challenging, and highly burden up on central executive WM resources. Notably, the most difficult questions (Q5, Q6, and Q9) share a common aspect: all require students to deal with verbal or visual material not directly presented in the slides. Hence, students have to process and evaluate textual or visual material that cannot be directly matched to what they observed or heard during the lesson, thereby requiring deeper cognitive processing and transfer of knowledge to novel stimuli. In Q5 the four alternative responses employ similar words that are different form the vocabulary used by the lecturer in the video-class or those reported in the slides. Similarly, in Q6 and Q9 students are presented with four pictures that do not appear explicitly in the video-class. Furthermore, Q6 is the sole visual question in which the four alternatives are everyday elements rather than sub-microscopic representations, so they are not specifically related to the chemistry domain. It could be argued that using verbal coding (e.g., the object names) instead of visual coding might lead to different results. During the recorded video-class, the hand is mentioned as an example of chirality, and when describing molecular structures, the lecturer specifies "helix structure" and shortly after, a "structure that wraps around itself". However, in Q6 the correct answer (regardless of representational format) requires the internalization of the concept of chirality, defined as an object or molecule that cannot be overlapped on its mirror image.

The prelaminar results of the correlational analysis, indeed, showed that higher performance in the CT was positively correlated with higher performance on the two WM tasks requiring both maintenance and manipulation of information (LST and IP). The little sample-size did not allow us to generalize these findings, but the fact that we observed significant correlation even with such small number of students is rather surprising. Therefore, these findings seemed to corroborate what previous studies have demonstrated: WM plays a crucial role in promoting chemistry learning even at a high level of education (e.g., Danili & Reid, 2004; Niaz, 1987; Reid, 2014; St Clair-Thompson et al., 2012). Lastly, another interesting aspect was the result of the correlation analysis between cognitive style (verbal or visual) and the partial score at the CT. Findings showed that high score at the CSQ (majorly verbal) were positively associated with the accuracy in textual questions, whereas low score at CSQ (majorly visual) were associated with the accuracy in the visual questions. In summary, the findings indicate that students who demonstrated a stronger aptitude for processing verbal material, as opposed to non-verbal material, tend to achieve higher scores in the textual section of the assessment. Conversely, individuals who demonstrated a stronger preference for processing visual information over verbal material attained higher scores in the visual questions.

The present preliminary findings did not authorize us to reach a strong conclusion yet, but they are important. They represent a first attempt to fill the lack of experimental protocols investigating cognitive processes involved in chemistry learning at higher educational levels within the Italian context. The major limitation was the sample size, but it had two main explanations: the protocol was long and lasted approximately three hours; students' participation was voluntary, and the assessment was not during class time (students dedicated part of their free time to take part in the research project).

3.2 Study 2: The role of visuospatial working memory in chemistry learning assessed in a sample of Italian undergraduate students

The present study has been designed consequently to the results and the conclusion acquired in Study 1. We reduced the assessment time focussing the attention on those tasks that seems to be more correlated to chemistry task' performance: the verbal and the visuospatial WM tasks that rely on maintenance and manipulation of information. Moreover, we managed to engage a wider sample of undergraduate students with the collaboration of many chemistry' professors (Professor Giampaolo Barone, Professor Riccardo Bonsignore, Professor Michele Cacioppo, Professor Elena Ghibaudi, Professor Enzo Laurenti, Professor Paolo Lo Meo, Professor Antonio Palumbo Piccionello, Professor Roberto Rabezzana, Professor Alessio Terenzi) that gave us the opportunity to administer the chemistry task during the scheduled lecture time. In a few classes we had two hours, and we were able to administer the WM assessment too.

This second study aimed to detect the involvement of both verbal and visuospatial WM components in a chemistry learning task. More precisely, we attempt to investigate the different relation (if any) between chemistry learning performance and verbal and visuospatial WM components. The assessment was carried out on a wide sample of Italian undergraduates.

Methods

Procedure

The present study was part of a wider research project "Exploratory investigation of the cognitive processes involved in learning chemistry" that was submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023). The assessment was implemented between March and December 2023, and it concerns two phases, which were administered separately:

- *Assessment of chemistry learning abilities:*
  This first administration was carried out in a collective session that lasted approximately 1 hour. During this time students were asked to perform a chemistry task (see Instrument, Study 1) and to answer a short anamnestic self-report questionnaire, so we were able to collect some personal details (age, gender, and type of degree course).
- *Assessment of WM and visuospatial abilities:*
  This second phase was administered during a collective session (duration approx. 1 hr) where students were asked to perform two WM tasks (a verbal and a visuospatial WM task), and to perform a test that measured students' visuospatial ability (mental rotation skills). Finally, we measured students' estimated IQ (Intelligence Quotient) score through the

Cattell's Fluid Intelligence Test, Scale 2 (Weiß, 2006). The 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.

This procedure and methodology were quite similar to the one used for the preparatory investigation (Study 1, pp. 61-62). The results of this previous preparatory study showed the adequacy of the methodological approach. Furthermore, in accordance with those findings, the administration time was reduced by narrowing down the number of WM tasks from four to two. In the present investigation, we only included the two WM tasks that significantly correlated with the chemistry performance.

Participants

The first phase (chemistry learning assessment) of the present experimentation involved 315 undergraduate Italian students with typical development (M_{age} = 20.2 years, SD_{age} = 5.32), who were enrolled at the first 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 (53.0%), 136 males (43.2%), 5 non-binary (1.6%), and 7 people (2.2%) who selected the following statement "I'd rather not answer this question". Students were enrolled in different scientific-related bachelor's 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 these science-related courses had, at least, one general chemistry class in their academic curricula, but most of them were not enrolled in chemistry degree courses. Moreover, the assessment of those students attending a chemistry degree course was implemented in the first two months of the first semester (first year), even them do not have further prior knowledge about the topic chosen for the chemistry task.

The self-selected sub-sample of students who took part in the second assessment phase involved 81 students. We excluded one single student because of the performance at the estimated IQ task (score < 75). Hence, the in-depth analysis on the relationship between chemistry performance and WM ability was computed on 80 students (M_{age} = 19.6 years, SD_{age} = 1.86). They were enrolled to different science-related degree course: Biotechnology (N= 4, 5%); Chemistry (N= 12, 15%); Natural science (N= 28, 35%); Biology (N= 20, 25%); Engineering (N= 16, 20 %); additional information is reported in Table 3.2.1.

Table 3.2.1 Demographic features of students' sub-sample (N = 80): number (N) and percentage (%) of gender distribution, mean (M) and standard deviation (SD) of the estimated Intelligence Quotient (IQ).

	Gender				Estimated IQ	
	Female	Male	Non-binary	NA	*M*	*SD*
N	36	40	1	3	104.3	13.03
(%)	(45 %)	(50%)	(1.3%)	(3.7%)		

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

Instruments

Chemistry Task (CT)

This task aims to assess students' chemistry learning ability: students watch a recorded video-class about liquid crystals, and after that, they answer a short final test (10 multi-choice questions – 5 textual and 5 visual). The detailed description of the task is reported in the Instrument section of Study 1 (pp. 62-68). The test was administered online using the Qualtrics platform.

The final score was obtained summing up the number of correct answers (maximum score = 10). Furthermore, the partial scores (textual and visual) were measured by summing up the correct responses for the textual and the verbal questions separately (maximum score = 5 for both cases). Finally, for the present study also the partial scores factual vs. conceptual have been computed. The factual items are Q1, Q4, Q7, and Q8 (maximum score = 4) and conceptual ones are Q2, Q3, Q5, Q6, Q9, Q10 (maximum score = 6). In order to be able to compare these two scores we muted them as percentage scores (see below).

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

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

Listening Span Task (LST) – Verbal WM

The Italian version of the Listening Span Task – LST (De Beni et al., 2008) was used to assess students' verbal WM. In this task students listened to and declared the truthfulness of a series of statements (from two sentences up to six), and after each set they were asked to recall the last word of each statement. A detailed description of this task was given in the Instrument section in Study 1 (p. 68).

This task measured students' ability to maintain and manipulate (update) verbal information. The final score was obtained summing up the number of words recalled in the proper order of presentation (maximum score = 20).

Imaginative Puzzle (IP) - Visuospatial WM

Imaginative Puzzle –IP (De Beni et al., 2008; Richardson & Vecchi, 2002) was administered in order to assess students' visuospatial WM. This task consisted of 27 items organized in nine levels (from level 2 to level 10, with three tasks per level) and students were asked to mentally reassemble a picture of a familiar object shattered in multiple pieces. A detailed definition of this task was reported in the Instrument section of Study 1 (pp. 68-69).

The final score was measured summing up the level-number of the most three complex levels successfully completed by the student (maximum score = 30).

Mental Rotation Test (MRT) - Visuospatial ability

In this second study the MRT (Peters et al., 1995; Vandenberg & Kuse, 1978) was included in the cognitive processes assessment. The MRT consisted of 24 items (12 item part 1 and 12 item part 2), and each one required the students to observe a 3D target figure (assembled cubes) finding out among four alternatives the two that are an identical rotated version of the target (see Figure 3.2.1). Therefore, the correct answers represented the same structure of the target, but it is shown in a rotated position.

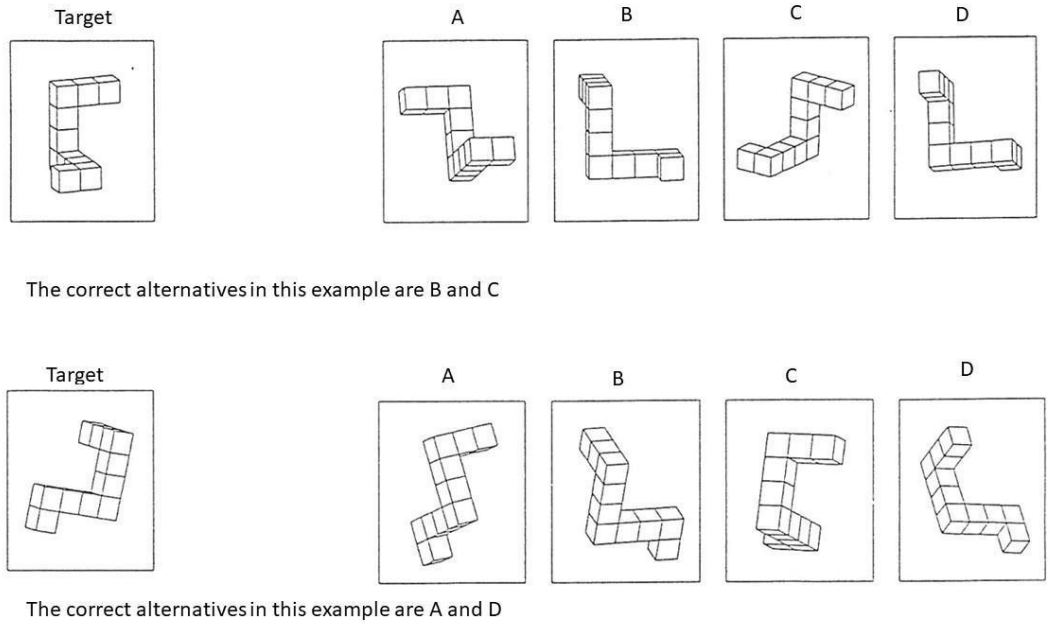


Figure 3.2.1 Examples of the items of the MRT (Peters et al., 1995; Vandenberg & Kuse, 1978).

The MRT is time-limited, and it lasted 6 minutes (3 min. for part 1 and 3 min. for part 2). We administered both part 1 and part 2, and 1 point was given for each proper identification. The final score was measured summing up the number of correct identifications given by the students (maximum score = 48).

Estimated Intelligence Quotient (Estimated IQ)

In the present investigation we also administered Cattell's Fluid Intelligence Scale (Weiß, 2006), which allowed us to measure an estimated Intelligent Quotient (IQ) score. The manual

includes two different scales (part 1 and part 2) and the conversion tables provide an estimated IQ measure either if only one of the two scales (part 1 or part 2) or the entire test (part 1 + part 2) is administered. Both scales consist of four different types of problems, and students are asked to solve as many problems as possible for each set in a limited-time period. The type of problem is the same for part 1 and 2, but the difference is the number of queries for each set and the time. Part 2 has less problems and shorter times than part 1, therefore only part 2 was employed. The first set of problems was called *Series* (12 items, 3 min., maximum score = 12): students watched a sequence of three items; then, they had to find items that among the five given alternatives fit and complete the series. The second set was the *Classification* (12 items, 3 min., maximum score = 12): students were asked to choose the item that conflicts with the others, among a set of five items. The third class was called *Matrix* (12 items, 3 min., maximum score = 12): students needed to individuate between five alternatives, the one that accurately completes a given matrix. The last typology was *Analogies* (9 items, 3 min., maximum score = 9): students observed a target image that included some geometrical figures and one/two black dot/dots placed at a specific position with respect to the figures; students should choose, among five alternatives reporting only the geometrical shapes, the one where dots could be placed in an analogous position as in the target. An example of each type of problem is reported in Figure 3.2.2.

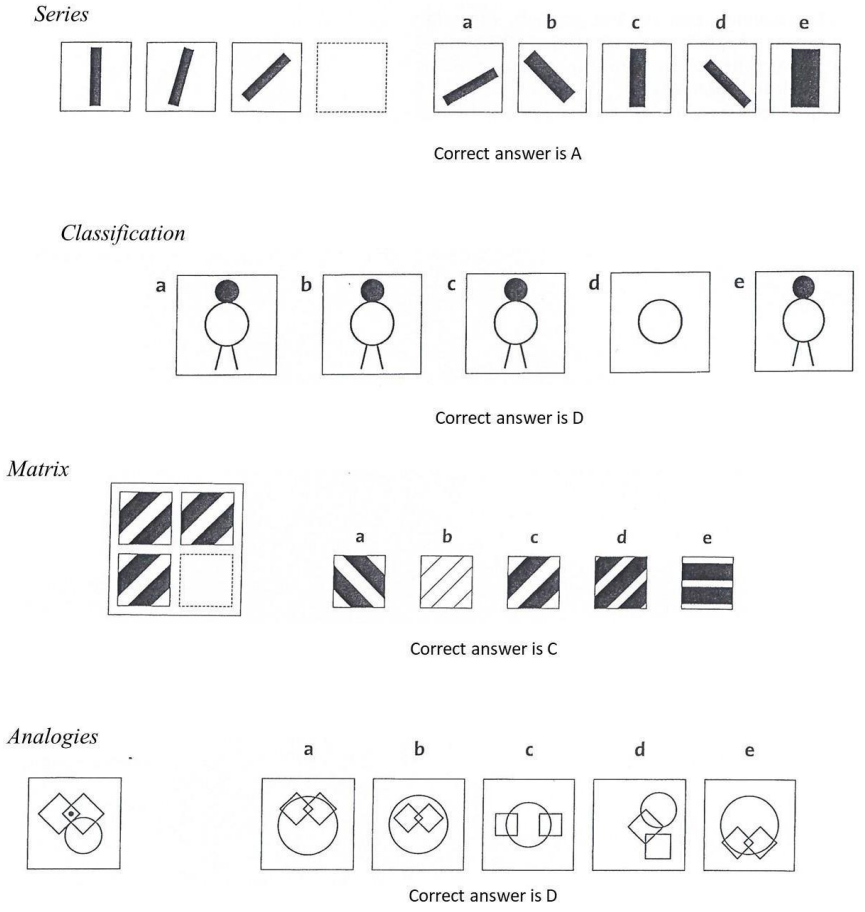


Figure 3.2.2 Examples of the item for each typology of problem included in the Cattell's Fluid Intelligence Scale (Weiß, 2006)

The final score was obtained counting the number of right answers (maximum score =45), and it was transformed into the estimated IQ score, according to the normative tables included in the manual. Overall, the internal consistency of the current sample was good ($\alpha = .78$).

Data Analysis

First, we analysed students' performance (N = 315) in the CT. Descriptives statistics (mean and standard deviation) of the total score, and the partial scores (textual and visual) were calculated.

Second, we measured descriptive statistics of the students' performance in the cognitive tasks (LST, IP, MRT and estimated IQ). Finally, we explored the relationship between CT and cognitive tasks performance (N = 80) implementing a correlation analysis and a linear regression analysis. These analyses pointed out a significant relationship between visuospatial WM and CT scores. Hence, we decided to examine in depth this aspect to determine whether there are some differences between textual and visual questions based on students' visuospatial WM ability. Consequently, we divided the sub-sample of 80 students in three groups, according to their performance at the IP task (low: IP $\leq$ 21; medium: 22 $\geq$ IP $\geq$ 27; high: IP $\geq$ 28) and we computed two separate (one for the type of questions) one-way non-parametric ANOVAs (Kruskal-Wallis) and we compared how differently these three groups performed in textual and visual questions. We implemented the non-parametric tests because the variables do not follow a normal distribution (see Shapiro-Wilk test results in Table 3.2.2). The same comparison has been made for the factual and the conceptual questions. In this last investigation we compared the percentage of accuracy because the factual questions are 4, whereas the conceptual ones are 6.

Data analysis was computed with the Jamovi Project Version 2.3 (2022).

Results

Students' CT performance

The CT was administered to the whole sample (N = 315) and both the total score (max score = 10) and the partial scores (textual and visual - max score = 5 each) were calculated. Descriptive statistics (mean and standard deviation) were computed for the total score, the textual questions, and the visual questions. The results are reported in Table 3.2.2.

Table 3.2.2 Mean (M),standard deviation (SD) and median for the accuracy (number of correct answers) in the total score and the partial scores (textual and visual) of the CT

Correct answers				Skewness	Kurtosis	Shapiro-Wilk	
	M	*SD*	*Median*			*W*	*p*
Total score	5.75	1.83	6	-.24	-.18	.97	< .001
Textual score	3.44	1.15	4	-.60	-.07	.90	< .001
Visual score	2.31	1.18	2	.01	-.66	.93	< .001
Factual	67.14%	23.43%	75%	-.48	-.21	.88	< .001
Conceptual	51.27%	21.98%	50%	-.06	-.47	.95	< .001

These descriptive statistics were quite similar to those observed in the preparatory investigation (Study 1, pp. 70). Additionally, the present descriptive statistics showed that students' performance was higher in textual questions compared to the visual ones. Therefore, we compared these two scores with the Wilcoxon test (the non-parametric alternative to the t Student' test). The results proved that textual and visual scores are statistically different, W= 27193, p < .001, effect-size = 0.79.

A further item-related analysis was carried out. More precisely, students' accuracy for each of the ten questions was calculated as the ratio between the number of correct answers and the number of total answers (315). These data are reported in Table 3.2.3.

Table 3.2.3 Percentage of students' accuracy in each item of the CT

	Textual questions					Visual questions				
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Percentage of accuracy	74.9	76.8	72.1	84.4	35.6	38.4	41.6	67.7	35.6	49.2

As it can be observed in Table 3.2.3, neither floor (percentage of accuracy = 0%) nor ceiling (percentage of accuracy = 100%) effects are present. This result is in accordance with previous results of the preparatory investigation. Additionally, the percentage of accuracy for each item seemed to highlight again a distinct trend in textual vs. visual questions: students' accuracy reached higher scores in the textual group of questions (Q1-Q5) than in the visual one (Q6-Q10). However, it should be noted that some questions do not fit this pattern, for example Q5 reaches a much lower score compared to other textual questions, and on the other hand Q8 the percentage of accuracy is higher compared to other visual questions.

This different trend in students' accuracy both in textual and visual questions was partially due to the different level of understanding that those questions need. The ten questions, indeed, concern four factual questions (Q2, Q4, Q7, Q8) and six conceptual ones (Q1, Q3, Q5, Q6, Q9, Q10). The former were defined as questions in which the proper answer mainly relies on the

recall of information; whereas conceptual ones were those that required the student to carry out further reasoning in order to reach a deep-level understanding. The mean percentage of accuracy in the factual ones was 67.1% (*SD* = 23.4%) and in the conceptual ones was 51.3% (*SD* = 22.0%). The non-parametric alternative to the t Student' test was revealed that students performed significantly better in the factual question compared to the conceptual ones, *W*= 34831, $p < .001$, effect-size = 0.64.

Relationship between CT performance and cognitive tasks

This second study aimed to investigate the relationship between students' CT performance and their cognitive abilities. As explained in the procedure section, the present analysis involved a self-selected sample of students (*N* = 80), who voluntarily agreed to adhere to the further investigation.

Descriptive statistics (mean and standard deviation) of students' performances were computed, and their relationship was investigated with a correlational analysis. We used the Spearman correlation analysis, because the distribution of the CT's score did not follow the normality criteria. These results are reported in Table 3.2.4.

Table 3.2.4 Mean (M), standard deviation (SD), and correlation analysis between all the variables.

				Spearman's Rho						
Task	*M*	*DS*	*Median*	1	2	3	4	5	6	7
1. CT Total	6.16	1.77	6	1						
2. CT Textual	3.49	1.23	4	.78**	1					
3. CT Visual	2.67	1.08	3	.70**	.15	1				
4. Estimated IQ	104.3	13.03	106	-.08	-.12	.02	1			
5. IP (visuo-spatial WM)	24.8	4.03	26	.39**	.30*	.27*	.36*	1		
6. LST (verbal WM)	17.1	2.77	18	.03	.07	-.01	.08	.11	1	
7. MRT (mental rotation)	24.9	8.55	26	-.03	-.01	-.07	.23	.23	.06	1

Note. * p < .05; ** < .001. CT = Chemistry task; IQ = Intelligence Quotient; IP = Imaginative Puzzle; LST = Listening Span Task; MRT = Mental Rotation Test

The correlational analysis pointed out a strong and positive correlation between CT Total scores and CT Textual score, as well as between CT Total and CT Visual scores. Additionally, it was observed a moderate and positive correlation between IP and CT performance (both total and textual scores), and a weak positive correlation between IP and CT visual scores. Finally, a moderate positive correlation had been found between IP score and Estimated IQ score.

Overall, the correlational analysis findings showed a significant relationship between CT scores and visuospatial WM performance. Hence, we investigated further the relationship between CT performance, and students verbal and visuospatial WM performance computing a linear regression analysis. CT Total score was considered as the dependent variable, whereas IP (visuo-spatial WM) and LST (verbal WM) scores were included as predictors. We also included as a predictor the interaction between IP and Estimated IQ score, because the correlation analysis showed a significant relationship. The results of the linear regression analysis are reported in Table 3.2.5.

Table 3.2.5 Results of Linear Regression Analyses

	B	*SE*	*t*	*p*	β	*95% IC*	
Intercept	1.77	1.66	1.07	.290			
IP	0.25	0.09	2.74	.008	.30	.08	.52
LST	0.04	0.07	0.54	.592	.03	-.18	.25
IP*Estimated IQ	-0.00	0.00	-1.48	.143	-.12	-.36	.11
	F (3,76) = 3.49, p = .020, R^2 *adjusted* = *.086*						

Note. CT = Chemistry Task; IP = Imaginative Puzzle; LST = Listening Span Test; IQ = Intelligence Quotient (IQ)

The linear regression analysis corroborated the results of correlation analysis. In particular, it pointed out that the CT performance was related with students' visuospatial WM performance. Conversely, the verbal WM component was not significantly related to chemistry learning performance in this task. Finally, no significant effect of the interaction between IP and estimated IQ was found.

We concluded the present investigation exploring in depth the relationship between CT performance and visuospatial WM. We divided the sub-sample in three groups according to their performance at the visuo-spatial WM task (IP). Therefore, we had: "low" with an IP score ≤ 21; "medium" for 22 > IP score > 27; and "high" for an IP score ≥ 28. Consequently, we compared how these three groups perform in the partial scores (textual vs. visual, and factual vs. conceptual) of the CT. Four separated one-way non-parametric ANOVA (Kruskal-Wallis test) were computed one for each partial score. The aim was to observe whether students with

different visuospatial WM abilities perform differently in textual and in visual questions, or in factual and conceptual questions based on their visuospatial WM abilities.

The three groups performed differently in textual and in visual questions (see Figure 3.2.4).

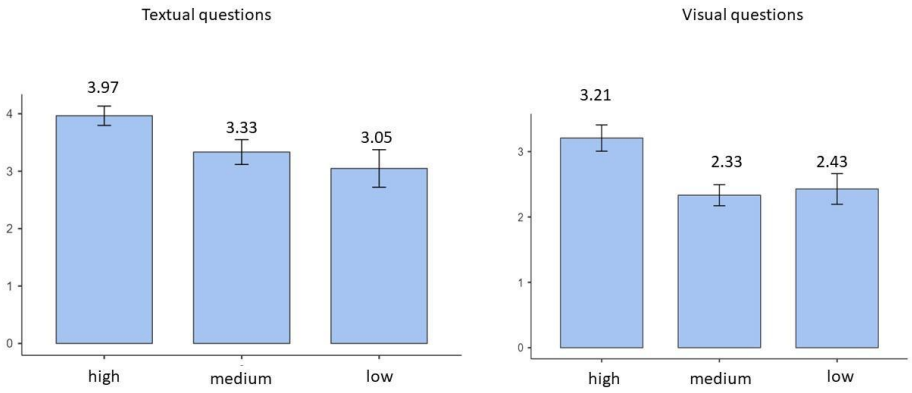


Figure 3.24 Mean of CT Textual and Visual scores in the three groups (low, medium and high IP score).

The Kruskal-Wallis test on textual questions showed a significative effect of the IP group $\chi^2(2) = 6.67$, $p = .036$, $\varepsilon^2 = .084$. Dunn's pairwise tests adjusted for Bonferroni pointed out no significant difference between the three groups, although the comparison between the high and low groups showed a trend toward significance ($p = .057$).

The Kruskal-Wallis test on visual questions revealed a significative effect of the IP group $\chi^2(2) = 9.54$, $p = .008$, $\varepsilon^2 = .121$. Dunn's pairwise tests adjusted for Bonferroni showed a significant difference between high and medium groups ($p = .012$). The comparison between high and low groups showed a marginally non-significant difference ($p = .060$), whereas no significant effect was observed between medium and low groups ($p = .996$).

Finally, the three groups performed differently in factual and in conceptual questions (see Figure 3.2.5).

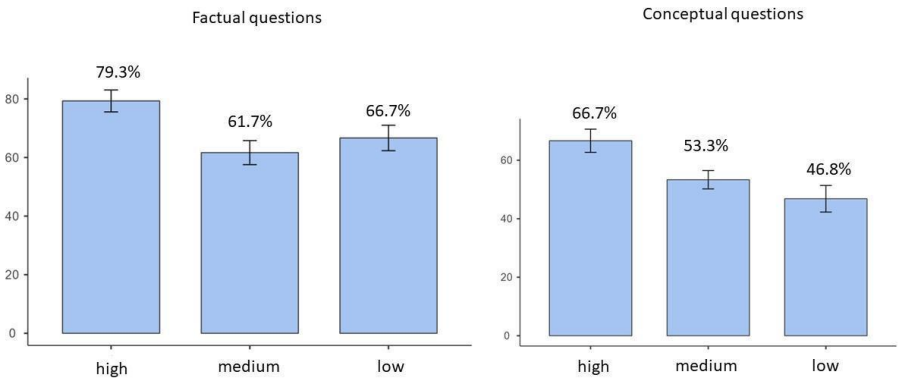


Figure 3.25 Mean of CT Factual and Conceptual percentage of accuracy in the three groups (low, medium and high IP score).

The Kruskal-Wallis test on factual questions showed a significative effect of the IP group $\chi^2(2) = 9.36$, $p = .009$, $\varepsilon^2 = .119$. Dunn's pairwise tests adjusted for Bonferroni pointed out a significant difference between high and medium groups ($p = .012$). Whereas no significative differences were found between high and low groups ($p = .104$) or between medium and low groups ($p = .613$)

The Kruskal-Wallis test on conceptual questions revealed a significative effect of the IP group $\chi^2(2) = 10.31$, $p = .006$, $\varepsilon^2 = .131$. Dunn's pairwise tests adjusted for Bonferroni showed a significant difference between high and low groups ($p = .010$). The comparison between high and medium groups showed a marginally non-significant difference ($p = .058$), whereas no significant effect was observed between medium and low groups ($p = .381$).

Overall, this further investigation confirmed that students with higher visuospatial WM ability performed better than those with lower ability.

Discussion

This second study extended previous investigation, and it provided interesting results proving the different involvement of verbal and visuospatial WM components in explaining undergraduates' performance in a chemistry task. This study focused on disciplinary knowledge and cognitive processes, hence the assessment concerned both a chemistry task and several cognitive tasks.

The CT used in the present and in previous investigation aimed to tackle some specific abilities. More precisely, the video-class on liquid crystals was designed by a multidisciplinary

pool of chemistry and psychology experts and its main goal is to create an ecological context where students must deal with some basic chemical issues (e.g. chirality, molecular and supramolecular structures, isometry, molecular geometry, molecular dynamics, etc.). Additionally, the chosen topic had a motivational strength, since liquid crystals were highly related to students' experiential world as they were part of many technological devices (e.g., cell phone screens, digital watch screens, etc.). We acknowledge that the chosen topic (liquid crystals) presents several elements of complexity and it was intentional: we selected a topic that exceeds the standard first-year curriculum because our aim was to evaluate how students' approach and reason through an unfamiliar and higher-level concept, rather than to assess the specific content knowledge expected of first-year university students.

At first, an analysis of CT performance was computed on a sample of Italian undergraduates enrolled in a scientific bachelor. It showed that students performed better in the textual questions than in the visual ones. However, this difference was not simply due to a major degree of difficulty of the visual questions, since they were balanced both in terms of type of knowledge (factual or conceptual) and type of cognitive processes (decoding, recalling, inhibition and interference) involved. The accuracy seemed to be higher in questions that do not employ active manipulation nor complex conceptual issues (Q2, Q4, Q7, Q8 – factual questions); whereas students' performance was lower in those questions that need a deep-level comprehension of chemical issues (Q1, Q3, Q5, Q6, Q9, Q10 – conceptual questions). The statistical analysis confirmed that students' percentage of accuracy in factual questions is significantly higher compared to their accuracy in the conceptual ones. Therefore, students' performance both in textual and visual questions depends on the diverse mobilisation of cognitive abilities, and the most complex questions are those which require integration and manipulation of different information as it has been demonstrated by Crone et al. (2006). Lastly, these findings were consistent with those of our preliminary investigation (Study 1 of the present chapter). They confirmed the greater difficulty in conceptual questions requiring the students to process and evaluate material that cannot be directly matched to what they observed or heard during the video-class (such as in Q5, Q6 and Q9). However, due to the larger sample of students involved here, we are able this time to reach a more generalisable conclusions.

The correlational analysis pointed out that textual and visual scores were not significantly related, but they are both strongly and positively correlated with the total CT score. Additionally, it shows that the only cognitive task that was moderately and positively correlated to CT scores (total, textual and visual) was the IP task, the one that measured students' visuospatial WM ability. Whereas, estimated IQ and MRT were not significantly related to CT performance. The involvement of visuospatial WM was further confirmed by the results of the linear regression analysis, which proved that the only significant predictor of the Total CT score was the IP score. Whereas the LST and the interaction between IP score and Estimated IQ score were not significant. It should be noted that the amount of variance explained by the linear regression model was little (8.6%). This is not surprising when complex phenomena (such as chemistry learning) are considered. However, it is noteworthy that these results are intriguing as they suggest that the general cognitive ability (estimated IQ) do not explain the variance in students' performance in this CT. Instead, visuospatial WM components appear to be the only

significant factor. This is partially due to the fact that the topic of the CT (liquid crystals) asks the students to deal with chemical issues that relies on visuospatial abilities (chirality, molecular and supramolecular structures, molecular dynamics, etc.). Our results corroborated previous investigations that proved the importance of visuospatial abilities in promoting chemistry learning and performance (Carter et al., 1987; Pribyl & Bodner, 1987; Sorby et al., 2020) and proved that previous results obtained by Rhodes at al. (2016) among adolescents (visuospatial WM is more involved than verbal WM in chemistry learning) were valid among undergraduates too.

We concluded the study with a further investigation: we computed four separated non-parametric one-way ANOVAs (Kruskal-Wallis test) in order to observe if students with high, medium and low IP scores performed differently in textual vs. visual questions as well as in factual vs. conceptual questions. This in-depth analysis confirmed that students with higher visuospatial WM scores performed better in textual and in visual questions and comparing the effect-sizes it can be observed that the advantage is more evident in the visual questions. The pairwise tests confirmed a significant difference between high and medium groups in the visual questions only. Finally, the Kruskal-Wallis tests show that students with lower visuospatial WM abilities performed worse both in factual and in conceptual questions. In this second case, the pairwise tests reported a significant difference between high and medium groups in factual questions, and between high and low groups in the conceptual ones. Overall, these results suggested that undergraduates, who were not endowed with strong visuospatial WM ability, struggle more than others because they faced more difficulties in creating a mental representation of abstract concepts (such as the visualisation of molecular structures, molecular interactions, chiral centres, molecular symmetry, etc…). Consequently, these findings could have important implications on educational level: they seem to suggest that implementing and including visualisation tools (such as the use of dynamic representation instead of static images) might improve students' understanding of chemistry topic that strongly solicit visuospatial WM abilities. Because these visualisation tools could support students especially those with low visuospatial WM abilities who struggle in creating mental representations. Overall, these findings correlate very well with previous works that proved the crucial role played by WM and visuospatial abilities explaining 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). Furthermore, our study provided evidence of the different role played by verbal and visuospatial WM components in chemistry learning.

3.3 Study 3: Assessing chemistry learning in undergraduate students with typical development and with Specific Learning Disabilities (SLDs)

This third study investigated how undergraduate students with typical development and with Specific Learning Disabilities (SLDs) perform in a chemistry task. Thanks to the collaboration of Professor Roberta Cavaglià, Professor Elena Ghibaudi, Professor Enzo Laurenti, and Professor Barbara Sini, we were able to engage 45 undergraduate students with SLDs. They have been assessed using the same chemistry task employed in Studies 1 and 2, and their performance was then compared to that obtained by a sample of students with typical development ($N = 291$).

The present study aimed to detect the differences, if any, in the performance of students with typical development vs. with SLDs in a chemistry task.

Methods

Procedure

This study was part of a wider research project "Exploratory investigation of the cognitive processes involved in learning chemistry" that was submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023). The assessment was implemented between December and May 2024, and it involved 45 students with SLDs and 291 undergraduates with typical development (TD), collected between October 2023 and January 2024. Both groups were assessed with a chemistry task that was carried out with a collective session (duration approx. 1 hr) and few personal details (age, gender, and type of degree course) were also collected during this phase.

In the present study chemistry learning was assessed implementing the same procedure and methodology used in Studies 1 and 2. The data were collected in a collective session that lasted approximately one hour.

Participants

The present investigation involved 291 undergraduate Italian students with TD ($M_{age} = 20.3$ years, $SD = 5.56$) and 45 undergraduate Italian students with SLDs ($M_{age} = 20.3$ years, $SD = 1.98$). The main characteristics of the two groups are reported in Table 3.3.1.

Table 3.3.1 Gender and university of the students with typical development and with SLDs

	Gender				University	
	Female	Male	Non-binary	NA	Turin	Palermo
TD	172 (59.1%)	107 (36.8%)	5 (1.7%)	7 (2.4%)	140 (48.1%)	151 (51.9%)
SLDs	21 (46.7%)	20 (44.4%)	1 (2.2%)	3 (6.7%)	41 (91.1%)	4 (8.9%)
Total	193 (57.4%)	161 (37.8%)	6 (1.8%)	10 (3.0%)	181 (53.9%)	155 (46.1%)

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

Most of the students were enrolled in a scientific degree course (TD = 95% and SLDs = 69%) such as biotechnology, chemistry, natural science, biology, veterinary medicine, statistics and economics. Whereas the rest (TD = 5% and SLDs = 31%) were enrolled in a humanistic degree course such as education, psychology, theatre and acting studies.

The sample of students with SLDs included only those who are in possession of a certified clinical diagnosis of SLDs. According to the Italian legal criteria for SLDs (Law 170, 2010) and the Italian National Guidelines for SLDs (Istituto Superiore di Sanità [Italian National Institute of Health], 2022). The main criteria used for the diagnosis of SLD are: (i) academic achievement in specific areas (reading, writing, and/or arithmetic) below the 5th percentile, or more than 2 SD below average, when assessed using standardized tests; (ii) students' difficulties are not due to sociocultural, educational, emotional, intellectual, sensory, or neurological problems; and (iii) these specific impairments are persistent and are not due to environmental factors such as sociocultural disadvantage, lack of proficiency in the language or inadequate school education; and emotional factors like for example emotional deprivation or affective problems within the family context.

The students were asked to specify the type of impairment: 48% of students with SLDs have difficulties in reading and/or writing, the 9% of them have difficulties in mathematics, and the 43% have difficulties both in reading and/or writing and in mathematics.

Instruments

Chemistry Task (CT)

The CT aimed to assess students' chemistry learning ability, and a detailed description of the task is reported in the Instrument section of Study 1 (pp. 62-68 and p.75). It was ensured that both groups (students with TD and with SLDs) were assessed in the same way. Consequently, no adjustments were implemented for the students with SLDs. In line with previous administrations (Studies 1 and 2), students with and without SLDs were granted sufficient time for the completion of the final test.

The final score of the CT was obtained summing up the number of correct answers (maximum score = 10). In the present study, the partial scores were also examined, we measured textual vs. visual as well as factual vs. conceptual scores. Finally, for this third investigation we also collected an additional variable "Time" indicating the number of seconds employed to fulfil the CT final test.

Data Analysis

Data analysis was computed with the Jamovi Project Version 2.3 (2022). First, we ran a preliminary analysis investigating whether there were significant differences in students with SLDs' performance based on the type (impairments in reading/writing, in mathematics or both). Given the small number of the sample, we implemented a non-parametric comparison. Second, descriptive statistics (mean and standard deviation) of the total and the partial scores were computed both for students with TD and with SLDs. The two groups' performances were compared. Due to the non-normality of the variables, also in this case we implemented the non-parametric version of the ANOVA. Third, a correlational analysis was computed in order to investigate the relationship between time and CT scores (total, textual and visual) in the two groups. Finally, we defined, both for the SLDs and the TD group, a new variable "Group time", derived from the percentile distribution of the continuous variable "Time" (number of seconds employed to fulfil the final test) in the two groups, separately. According to the distribution we identified three levels: "slow" whose (time ≤ 25° percentile); "medium" for (25° percentile > time >75° percentile); "rapid" for (time ≥ 75° percentile). Because of the non-normality of the variables, we computed the non-parametric alternative to the two-way repeated measure ANOVA using the type of question (textual vs. visual) as within variable and the Group (TD vs. SLDs) and Group time as between variables.

Results

How students with TD and with SLDs perform at the CT

The group of students with SLDs included three different profiles: students with difficulties in reading and/or writing (48%), with difficulties in mathematics (9%), and with difficulties in both areas (43%). Therefore, we first investigated whether there were any differences in CT's performance according to the type of SLDs. We compared the three groups with the Kruskal-Wallis test (non-parametric alternative for the one-way ANOVA). The results of the analysis are reported in Table 3.3.2.

Table 3.3. 2 Mean (M) and standard deviation (SD) of students' with SLDs performance at the CT, separated for the three groups (with difficulties in reading and/or writing, in mathematics, and both areas) and compared with the non-parametric Kruskal-Wallis test.

	Reading and/or Writing		Mathematics		Both		Kruskal-Wallis test		
	M	*SD*	*M*	*SD*	*M*	*SD*	$\chi^2(2)$	*p*	ε^2
Total	5.80	1.99	6.25	2.99	5.33	2.09	0.43	.807	.010
Textual	3.00	1.08	3.25	1.71	3.06	1.35	0.31	.856	.008
Visual	2.80	1.47	3.00	1.41	2.28	1.36	1.46	.483	.036
Factual	65.0%	29.7%	68.8%	31.5%	66.7%	24.3%	0.07	.968	.002
Conceptual	53.3%	22.0%	58.3%	31.9%	44.4%	24.3%	1.56	.458	.038
Time	562	191	635	81	587	253	1.06	.589	.026

Note. Total = total score at CT (max. = 10); Textual = number of correct textual question (max. = 5); Visual = number of correct visual question (max. = 5); Factual = percentage of correct factual questions; Conceptual = percentage of correct conceptual questions; Time = seconds needed to fulfil the CT.

Overall, it was observed that the performance of the three groups was not statistically different. Hence, we concluded that the students with SLDs could be considered all together.

Secondly, we compared how students with TD and with SLDs performed at the CT. Descriptive statistics (mean and standard deviation) of the two groups were computed. The students' performance was measured as the number or the percentage of correct answers, and as the seconds needed to fulfil the CT (Time). The results are reported in Table 3.3.3.

Table 3.3. 3 Mean (M),standard deviation (SD) and median of students' performance at the CT, separated for the two groups (with TD and with SLDs)

	TD			SLDs			Mann-Whitney test		
	M	*SD*	*Median*	*M*	*SD*	*Median*	*U*	*p*	*Effect-size*
Total	5.78	1.76	6	5.64	2.07	6	6177	.536	.057
Textual	3.48	1.13	4	3.09	1.24	3	5337	.038	.185
Visual	2.30	1.16	2	2.56	1.39	2	6008	.359	.082
Factual	67.1%	23.8%	75%	66.7%	26.7%	75%	6531	.977	.003
Conceptual	51.7%	20.9%	50%	49.6%	23.7%	50%	6034	.384	.079
Time	547	144	540	573	202	589	6266	.643	.043

Note. TD = students with typically development; SLDs = students with Specific Learning Disabilities; Total = total score at CT (max. = 10); Textual = number of correct textual question (max. = 5); Visual = number of correct visual question (max. = 5); Factual = percentage of correct factual questions; Conceptual = percentage of correct conceptual questions; Time = seconds needed to fulfil the CT.

The two groups' performances were statistically compared with the Mann-Whitney test, which is the non-parametric alternative to the Students' t-test. Overall, the students with SLDs performed at the CT slightly differently from the group of students with TD, but this difference was statistically significant only for the Textual score.

Finally, we compared the percentage of accuracy for each single question of the CT separately for the two groups. We computed the Mann-Whitney test to see if there were any differences between the two groups. The results are reported in Table 3.3.4

Table 3.3. 4 Mean (M) and standard deviation (SD) of the percentage of accuracy for each of the ten questions of the CT, separated for the two groups (with TD and with SLDs) and compared with the non-parametric Mann-Whitney test.

	TD		SLDs		Mann-Whitney test		
	M	*SD*	*M*	*SD*	*U*	*p*	*Effect-size*
Q1	77.0%	42.2%	68.9%	46.8%	6018	.239	.081
Q2	77.0%	42.2%	64.4%	48.4%	5727	.070	.125
Q3	75.3%	43.2%	66.7%	47.7%	5985	.222	.086
Q4	84.9%	35.9%	75.6%	43.5%	5937	.117	.093
Q5	34.4%	47.6%	33.3%	47.7%	6480	.893	.010
Q6	40.5%	49.2%	53.3%	50.5%	5711	.107	.128
Q7	39.2%	48.9%	53.3%	50.5%	5621	.073	.142
Q8	67.4%	47.0%	68.9%	46.8%	6447	.839	.015
Q9	34.0%	47.5%	40.0%	49.5%	6156	.435	.060
Q10	48.8%	50.1%	50.1%	49.5%	5972	.273	.088

The analysis on the single questions pointed out that the percentages of accuracy of the two groups (with TD and with SLDs) were not statistically different.

Overall, the present comparative investigation showed that students with SLDs performed mostly as their peers with TD at this CT. However, students with SLDs were statistically less correct in the textual questions compared to the TD group.

Relationship between time and performance in the two groups

Firstly, we investigated the correlation between the total and the partial scores (textual, and visual) and the Time (seconds needed to fulfil the CT), separated for the two groups. The peculiarity of the CT is that it includes textual as well as visual questions. Due to the different profiles of students with TD and with SLDs it was interesting to investigate the differences (if any) between the time and the students' accuracy in the textual and in the visual questions.

The results are reported in Table 3.3.5.

Table 3.3.5 Results of the correlational analysis (Sperarman' rho) between Time and the total and partial scores at CT in the two groups (with TD and with SLDs)

	Time (student with TD)		Time (student with SLDs)	
	Spearman' rho	*p*	*Spearman' rho*	*p*
Total	.22**	< .001	.35*	.019
Textual	.28**	< .001	.14	.376
Visual	.06	.288	.40*	.007

Note. TD = students with typically development; SLDs = students with Specific Learning Disabilities; Total = total score at CT (max. = 10); Textual = number of correct textual question (max. = 5); Visual = number of correct visual question (max. = 5); Factual = percentage of correct factual questions; Conceptual = percentage of correct conceptual questions; Time = seconds needed to fulfil the CT.

The correlational analysis highlighted that in the group of students with TD time correlates positively and moderately with the total and the textual scores. Students with TD that employed more time to fulfil the CT were more accurate compared to those who answer faster in the total score and the textual questions. Finally, the relationship between Time and visual score was not significant in this group.

The results of the correlational analysis in the group of students with SLDs showed that Time correlated positively and moderately with the total and the visual scores, whereas the relationship between time and textual score was not significant.

Finally, we divided both the students with SLDs and with TD into three groups based on the time they take to fulfil the CT, see Table 3.3.6.

Table 3.3. 6 Distribution of students with TD and with SLDs in the three levels of the variable "Group time"

	Group time		
	Slow (Time ≥ 75° percentile)	Medium (25° percentile < Time < 75° percentile)	Rapid (Time ≤ 25° percentile)
Students with TD	N = 76	N = 181	N = 73
Students with SLDs	N = 12	N = 22	N = 11

We computed the non-parametric alternative to the repeated measure ANOVA using the type of question (textual vs. visual) as within variable and the Group (TD vs. SLDs) and Group time as between variables. Given the deviation of the data from a normal distribution, a statistical technique known as the Aligned Rank Transform (ART) was employed. This methodology involves the alignment of the data to remove the effects of various factors, followed by the ranking of the aligned values. This allowed us to implement standard ANOVA procedures on the ranked data, thereby facilitating the testing of main effects and interactions in a manner that is robust to non-normality and outliers.

The analysis highlighted a significant effect of the "Type of questions", $F(1, 660) = 59.55$, $p < .001$, $\eta^2 = .784$, in particular, students performed better in textual ($M = 3.43$) rather than in visual questions ($M = 2.33$). In addition, a significant effect of the "Group time" was observed, $F(2, 660) = 3.71$, $p = .025$, $\eta^2 = .114$: slow^{a} > medium^{a,b} > rapid^{b} . In other words, those who responded more quickly tended to make more mistakes. By contrast, no significant effect of the Group (TD vs. SLDs) was found, $F(1, 660) = .27$, $p = .605$, $\eta^2 = .004$. Furthermore, no significant interaction effect was found between Group*Group time $F(2, 660) = .26$, $p = .767$, $\eta^2 = .008$; nor between the Type of question*Group, $F(1, 660) = 1.78$, $p = .183$, $\eta^2 = .028$; nor between the Type of question*Group time, $F(2, 660) = .16$, $p = .854$, $\eta^2 = .005$. Finally, no significant interaction was found between Type of question*Group*Group time, $F(2, 660) = 1.81$, $p = .164$ $\eta^2 = .057$.

The average score for each group is reported graphically (see Figure 3.3.1).

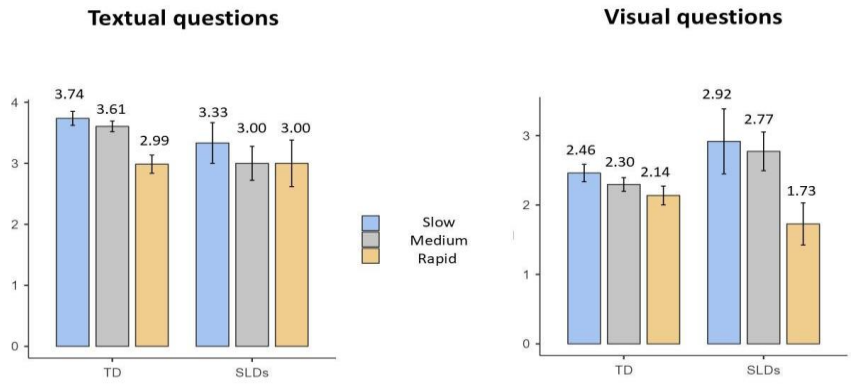


Figure 3.3. 1 Mean of CT Textual and Visual scores in the three groups (slow, medium and rapid group).

Finally, we reported in Figure 3.3.2 a graphical representation of students' performance in textual and visual question separated per Group and Group time.

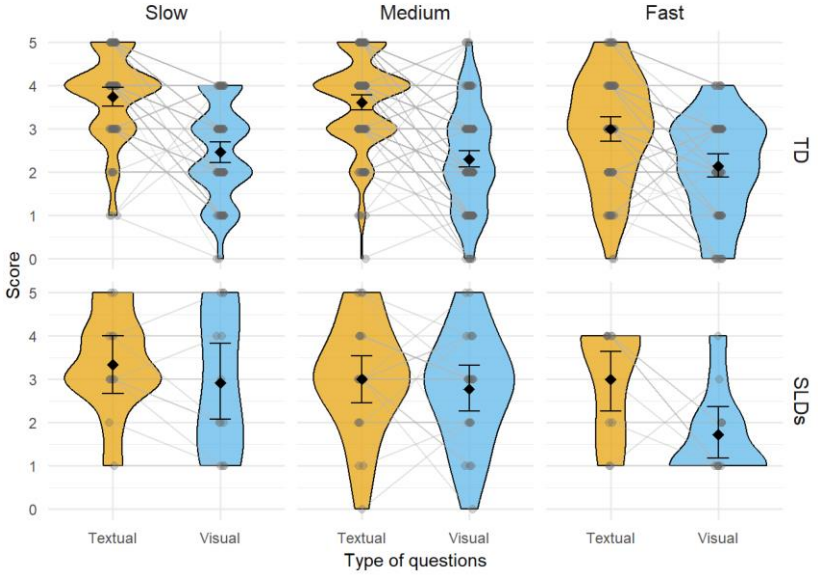


Figure 3.3.2 Graphical representation of students' performance on textual and visual questions, separated by Group time (Slow, Medium and Fast) and Group (students with TD and with SLDs).

Discussion

This study compared how undergraduate students with TD and with SLDs perform in a chemistry task (CT). Previous studies in chemistry education mainly aimed to investigate chemistry learning ability among students with TD (e.g., Kan & Akbaş, 2006; Pribyl & Bodner, 1987; Rhodes et al., 2016; Stamovlasis & Papageorgiou, 2012; Stieff et al., 2012). The present investigation, instead, focused the attention on the students' performance in a CT, and it aimed at catching differences and similarities between undergraduates with TD and with SLDs. A

wide sample of students with TD (N= 291) and 45 students with SLDs were assessed with a CT, both groups followed the same procedure. Therefore, students with SLDs were not allowed to benefit from any compensatory or dispensatory tool.

Students' performance was assessed in terms of accuracy and time employed by the student to fulfil the CT. The two groups were compared, and the results pointed out no significant difference between the two groups for most of the scores. This result is coherent with recent literature suggesting that students with SLDs do not have particular problems when they have to acquire knowledge from a video-class (Frinco et al., 2025). The only significant difference was observable in the textual question score. Moreover, the descriptive statistics highlight that the standard deviation (for each variable) is bigger among students with SLDs than among those with TD. This proved that their performance is more heterogeneous compared to the one obtained by their pair with TD. Furthermore, these comparative analyses confirmed that students with SLDs keep struggling more than students with TD especially when they have to deal (process and manipulate) textual information (Bogdanowicz et al., 2014; Montesano et al., 2020). Conversely, students with SLDs performed slightly better compared to peers with TD in the visual questions, even though these differences are not significant.

Thereafter, we investigated the relationship between time and accuracy in the two groups. It is evident that, due to the neurobiological nature of SLDs, the challenges related to the automatization of learning processes (reading, writing and/or mathematics) persist throughout adulthood. The majority of students manage to overcome this issue by developing a range of strategies; however, they frequently exhibit slower information-processing speed compared to their peers with TD (Hatcher et al., 2002; Pizzigallo et al., 2023; Toffalini et al., 2017). Our results pointed out that students with SLDs were slower than those with TD, but the difference was not significant. Therefore, we decided to deepen the relationship between time employed to fulfil the CT and accuracy. Correlation analysis results highlighted that time correlated positively with the total score of the CT both among students with and without SLDs. Nevertheless, the findings showed that the relationship between time and accuracy in the textual and in the visual questions was different for the two groups Time correlated positively with textual score among students with TD and with visual score among those with SLDs. In other words, students with TD that use more time to fulfil the CT were more accurate on textual questions; however, time appeared to have no effect on their accuracy in visual questions. In contrast, the pattern was reversed for students with SLDs. For these students, performance on textual questions did not improve even when they spent more time to fulfil the CT, suggesting that additional time was not sufficient to compensate for their verbal processing difficulties. We hypothesised that their weaknesses in the automatization of learning processes affect their performance, especially when the task highly overload reading and verbal information processes (such as the case of textual question). On the contrary, students with SLDs that answered faster were more inaccurate in visual questions compared to those who took more time.

Finally, the non-parametric alternative to the repeated measure ANOVA showed that both students with and without SLDs performed worse in the visual than in the textual questions,

corroborating the correlational analysis results. Furthermore, it highlighted that students who responded more quickly tended to be less accurate. Unfortunately, no significant interaction effect between Group (TD vs. SLDs), Time (Slow, Medium, Fast), and Question Type (Textual vs. Visual) was observed, which would have supported the results of the correlational analyses. This absence of interaction may be due to the imbalance in group size between students with and without SLDs.

Overall, these findings are particularly valuable as they, for the first time, focus the attention on the differences between students with and without SLDs. They pointed out that students with SLDs perform similarly to students with TD in our CT (designed to assess chemistry learning ability among undergraduates). In addition, taken together our findings seem to suggest that time could be a precious resource for students with SLDs. A further interesting result emerges looking at the graphs, that when the learning task includes questions that do not overload reading processes (such as the visual questions), students with SLDs can overcome students with TD accuracy.

3.4 Study 4: Working memory and chemistry learning: a preliminary investigation of differences between students with typical development and with Specific Learning Disabilities (SLDs)

This fourth study investigated the relationship between cognitive processes and chemistry learning among students with typical development (TD) and with Specific Learning Disabilities (SLDs). More precisely it studied the differences (if any) between visual and verbal working memory and chemistry learning in the two groups.

Methods

Procedure

The present investigation was part of a wider research project "Exploratory investigation of the cognitive processes involved in learning chemistry" that was submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023). The assessment was implemented between March 2023 - June 2024 and it concerns two phases, which were administered separately:

- *Assessment of chemistry learning abilities:*
  Chemistry learning ability has been assessed asking the students to perform a chemistry task (see Instrument, Study 1). The task was administered in a collective session that lasted approximately 1 hour. During this time students were also asked to fulfil a short anamnestic questionnaire, so we were able to collect some personal details (age, gender, and type of degree course).

- *Assessment of WM and visuospatial abilities:*
  This second phase was administered during another collective session (duration approx. 1 hr) where students were asked to perform two WM tasks (a verbal and a visuospatial WM task) the same implemented in Study 2 (see pp. 68-69). Finally, we measured students' estimated IQ (Intelligence Quotient) score through the Cattell's Fluid Intelligence Test, Scale 2 (Weiß, 2006), for a more detailed explanation see Study 2 pp. 77-78 . The 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.

This procedure and the methodology mostly the same implemented Study 2 (see, section Procedure of Study 2, p. 74).

Participants

The present investigation involved 87 undergraduate Italian students with TD (M_{age} = 19.41 years, *SD* = 2.29; 50 females and 37 males) and 21 students with SLDs (M_{age} = 20.19 years, *SD* = 1.86; 15 females and 6 males). These students were all enrolled at the University of Palermo (N= 19 among the students with TD) or at the University of Turin (N= 68 students with TD; N = 21 students with SLDs). The students with TD were all enrolled in a scientific-related bachelor's degree courses (such as Chemistry, Natural Science and Biotechnology). The sample of students with SLDs included undergraduates enrolled in scientific-related bachelor's degree courses (58%) as well as humanistic-related (29%) and health-related (13%) bachelor's degree courses.

The sample of students with SLDs included only those who are in possession of a certified clinical diagnosis of SLDs. The sample of students with SLDs included students with difficulties in reading and/or writing (38%), with difficulties in mathematics (10%), and with difficulties in both areas (52%). According to the Italian legal criteria for SLDs (Law 170, 2010) and the Italian National Guidelines for SLDs (Istituto Superiore di Sanità [Italian National Institute of Health], 2022), the main criteria used for the diagnosis of SLD are: (i) academic achievement in specific areas (reading, writing, and/or arithmetic) below the 5th percentile, or more than 2 SD below average, when assessed using relevant standardized tests; (ii) students' difficulties are not due to sociocultural, educational, emotional, intellectual, sensory, or neurological problems; and (iii) these specific impairments are persistent and are not due to environmental factors such as sociocultural disadvantage, lack of proficiency in the language or inadequate school education; and emotional factors like for example emotional deprivation or affective problems within the family context.

Due the results observed in Study 3 and in accordance with DSM 5 (APA, 2013) we considered students with SLDs as whole group.

Instruments

Chemistry Task (CT)

The CT was a complex learning task designed to assess university students' chemistry learning ability: students were asked to watch a recorded video-class about liquid crystals, and after that they had to answer a short final test (10 multi-choice questions – 5 textual and 5 visual). The detailed description of the task is reported in the Instrument section of Study 1 and 2 (pp. 62-68 and p.75). The test was administered online using the Qualtrics platform.

The final score was calculated summing up the number of correct answers (maximum score = 10). In addition, partial scores (textual and visual) were measured by summing up the correct responses for the textual and the verbal questions separately (maximum score = 5 for both cases).

Listening Span Task (LST) – Verbal WM

The Listening Span Task – LST (De Beni et al., 2008) was implemented to assess students' verbal WM. Students listened to and were asked to decide the truthfulness of a series of statements (from two sentences up to six), and after each set of sentences they had to recall the last word of each statement. A detailed description of this task is given in the Instrument section in Study 1 (p. 68).

This task assessed students' ability to maintain and manipulate (update) verbal information. The final score was obtained summing up the number of words recalled in the proper order of presentation (maximum score = 20).

Imaginative Puzzle (IP) - Visuospatial WM

Imaginative Puzzle – IP (De Beni et al., 2008; Richardson & Vecchi, 2002) evaluated students' visuospatial WM. This task consisted of 27 items organized in nine levels (from level 2 to level 10, with three tasks per level). Students must mentally reassemble a picture of a familiar object shattered in multiple pieces. A detailed definition of this task is reported in the Instrument section of Study 1 (pp. 68-69).

The final score was measured summing up the level-number of the most three complex levels successfully completed by the student (maximum score = 30).

Estimated Intelligence Quotient (Estimated IQ)

Cattell's Fluid Intelligence Scale (Weiß, 2006) allowed us to have an estimated Intelligent Quotient (IQ) of the students who took part in the investigation. The manual consists of two different scales (part 1 and part 2) and it includes conversion tables that allow us to calculate an estimated IQ score either if only one of the two scales (part 1 or part 2) or the entire test (part 1 + part 2) is administered. Both scales present four different types of problems, and students

are asked to solve as many problems as possible for each set in a limited-time period. The typology of problems are *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). For a better explanation of each type of problem see Study 2 (pp. 77-78).

The final score was obtained counting the number of right answers (maximum score =45), and it was transformed into the estimated IQ score, according to the normative tables included in the manual. Overall, the internal consistency of the current sample was good ($\alpha = .72$).

Data Analysis

Data analysis was computed with the Jamovi Project Version 2.3 (2022). Descriptive statistics (mean and standard deviation) of each variable were computed both for students with and without SLDs. Therefore, we compared the two groups in the cognitive tasks and in the CT performance. The variables did not have a normal distribution; hence, we compared the two groups implementing the non-parametric tests.

In addition, we computed two separated correlational analyses (one for the group of students with TD and the other one for the sample of students with SLDs) and we deepened the relationship between WM abilities and CT performance computing two separated linear regression analyses.

Results

We compared how students with TD and with SLDs performed at the cognitive tasks and the chemistry task (CT). Descriptive statistics (mean and standard deviation) of the two groups as well as non-parametric comparisons are reported in Table 3.4.1

Table 3.4.1. Mean (M), standard deviation (SD), median and non-parametric comparisons of students with typical development (TD) and with SLDs performances

		TD			SLDs			Non-parametric comparisons	
		M	*SD*	*Median*	*M*	*SD*	*Median*	*Mann-Whitney's U*	*Effect size*
Cognitive tasks	LST – verbal WM	17.8	2.20	18	15.3	4.24	16	389*	0.365
	IP – visual WM	24.1	3.82	25	24.9	3.60	26	797	.084
	Estimated IQ score	104.0	12.00	103	107.1	15.67	111	735	.196
Chemistry task (CT)	Total	5.87	1.72	6	5.48	2.09	6	800	.124
	Textual	3.37	1.23	4	3.14	1.31	3	817	.106
	Visual	2.51	1.02	3	2.33	1.28	2	825	.097
	Factual	70.4%	23.36%	75%	61.9%	28.08%	75%	762	.166
	Conceptual	50.96%	20.86%	50%	50.00%	25.28%	50%	871	.047
	Time	487	127	485	553	128	549	646*	.293

Note. * $p < .05$; ** $p < .01$; *** $p < .001$

Overall, students with SLDs reached lower scores in the verbal WM tasks compared to students with TD; whereas the two groups have equivalent competences in visuospatial WM and in estimated IQ.

Additionally, it was observed that students with SLDs did not underperform in terms of accuracy compared to students with TD. However, it emerged that these students awerere statistically slower compared to students with TD. This aspect was quite interesting: it pointed out that students with and without SLDs (with the same visuospatial WM abilities and comparable general intelligence ability) could reach similar chemistry learning outcomes, but the firsts need more time.

Correlational and linear regression analyses

The relationship between CT performance and cognitive abilities was investigated firstly with two separated (one for each group) correlational analyses. The main results are reported in Table 3.4.2.

Table 3.4. 2. Correlational analysis between CT total score and the cognitive abilities the two groups (with TD and with SLDs)

	TD				SLDs			
	Spearman's Rho				Spearman's Rho			
Task	1	2	3	4	1	2	3	4
1. CT Total	1				1			
2. Estimated IQ	-.07	1			.23	1		
3. LST – verbal WM	-.002	-.02	1		.36	.29	1	
4. IP – visual WM	.33**	.42***	.14	1	.57**	.53*	.55*	1

Note. * p < .05; ** p< .01; *** p < .001

The correlational analyses pointed out that visuospatial WM correlated positively with the accuracy in the CT (total score). Additionally, they underlined that the relationship was stronger in students with SLDs than in students with TD.

Finally, two separated linear regression analyses were computed, one for the students with TD (Table 3.4.3) and one for the students with SLDs (Table 3.4.4). In both cases the dependent

variable was the Total score at the CT and the predictors were: the Imaginative Puzzle (IP) score; the estimated IQ; Time (the time employed to complete the chemistry task); IP*Time; IP*estimated IQ. In the present model, Time was included as a predictor based on evidence from Study 3, which identified time as significantly associated with students' accuracy in the chemistry task. In addition, previous literature as well as the non-parametric comparisons indicating that students with SLDs were significantly slower further support the inclusion of Time as predictor in the model.

Table 3.4. 3 Results of Linear Regression Analyses for the students with TD

	B	*SE*	*t*	*p*	β	*95% IC*	
Intercept	-7.45	11.05	-0.67	0.502			
IP – visual WM	0.64	0.47	1.37	0.174	0.39	0.17	0.61
Estimated IQ	0.09	0.09	0.97	0.334	-0.18	-0.41	0.04
Time (in seconds)	-.0005	0.01	-0.03	0.976	0.10	-0.10	0.31
IP*Time	.000	.000	0.18	0.858	0.02	-0.20	0.24
IP*Estimated IQ	-0.005	0.004	-1.24	0.218	-0.13	-0.33	0.08
	F (5,81) = 3.14, p = .012, R^2 *adjusted = .162*						

Note. CT = Chemistry Task; IP = Imaginative Puzzle; LST = Listening Span Test; IQ = Intelligence Quotient (IQ)

Table 3.4.4. Results of Linear Regression Analyses for the students with SLDs

	B	*SE*	*t*	*p*	β	*95% IC*	
Intercept	50.60	29.089	1.74	0.110			
IP – visual WM	-1.33	1.198	-1.11	0.289	1.11	0.40	1.81
Estimated IQ	0.050	0.196	0.26	0.802	-0.54	-1.20	0.13
Time (in seconds)	**-0.12**	**0.049**	**-2.37**	**0.037**	**-0.38**	**-0.94**	**0.18**
IP*Time	**0.004**	**0.001**	**2.39**	**0.036**	**0.98**	**0.08**	**1.88**
IP*Estimated IQ	-0.005	0.008	-0.61	0.556	-0.14	-0.63	0.36
	F (5,11) = 4.54, p = .017, R^2 *adjusted* = .525						

Note. CT = Chemistry Task; IP = Imaginative Puzzle; LST = Listening Span Test; IQ = Intelligence Quotient (IQ)

Overall, the regression analysis with the students with TD showed that none of the predictors was significant. On the other hand, the regression analysis with the students with SLDs highlight that the model explained the 52.5% of variance and Time as well as the interaction between visual WM and Time are significant predictors. Time employed on filling the CT was negatively related to accuracy in students with SLDs. More precisely, the significant interaction (IP*Time) clarified that slower students with SLDs were less accurate than fast ones, but if slower students do have high visuospatial WM can reach and overperform students with TD, see Figure 3.4.1.

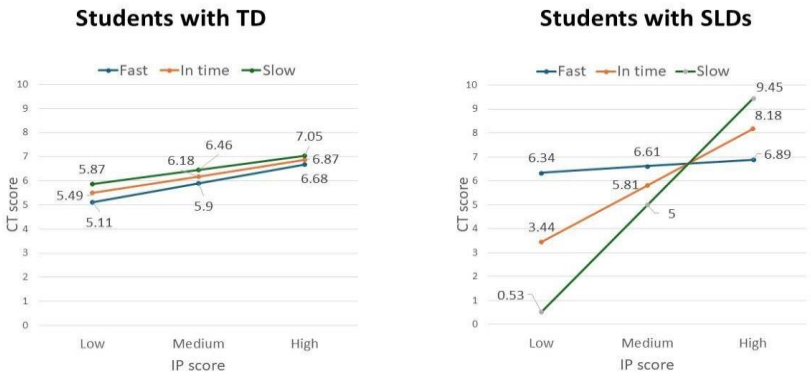


Figure 3.4.1 Interaction effect (IP score*Duration) among students with TD and students with SLDs.

Discussion

This forth study explored the different relationship between the WM components (verbal and visuospatial) and students' performance in a chemistry task (CT), investigating whether it was possible to observe differences among students with and without SLDs. Previous studies in chemistry education (e.g., Kan & Akbaş, 2006; Pribyl & Bodner, 1987; Rhodes et al., 2016; Stamovlasis & Papageorgiou, 2012; Stieff et al., 2012) mainly explored the relationship between cognitive processes and chemistry learning but only among students with TD. The present investigation aimed to fulfil this gap, pinpointing the attention on the undergraduate students with TD as well as on those with SLDs.

In order to successfully perform this chemistry task (CT) students needed to deal with some basic chemical issues (e.g. chirality, molecular and supramolecular structures, isometry, molecular geometry, molecular dynamics, etc.). The CT was assessed in the exact same way among students with and without SLDs, hence, the latter did not benefit from any adjustment. The current investigation involved 87 students with TD and 21 with SLDs with comparable general cognitive ability (estimated IQ). In accordance with literature (Callens et al., 2012; Pizzigallo et al., 2023; Toffalini et al., 2017) students with SLDs performed worse than students with TD in the verbal WM task, but there was no significant difference in the visuospatial WM task. This result was expected since students with SLDs in adulthood keep struggling in processing and dealing with phonological information (Callens et al., 2012; Pizzigallo et al., 2023). Additionally, we compared the two groups' performance at the CT in terms of accuracy and time to fulfil the task. The comparative analyses pointed out no significant difference in terms of accuracy, nevertheless students with SLDs were slower than those with TD. The accuracy result is consistent with Study 3 of the present chapter and with recent literature suggesting that students with SLDs do not have particular problems when they have to acquire knowledge from a video-class (Frinco et al., 2025).These results partially corroborated what we observed in Study 3: as students with SLDs were significantly slower compared to peers with TD. The fromer can benefit from having more time to complete a learning task even in the chemistry domain. This is true also in higher education where this subject reaches a high level of abstraction and students are constantly asked to deal with abstract concepts relying both on phonological and visuospatial processes. The present findings, indeed, did not replicate the performance pattern documented in Study 3, in which students with SLDs obtained a slightly and not significant better performance on visual questions compared to peers with TD. This discrepancy may be attributed to the limited sample size and substantial heterogeneity in students' performance, which was particularly pronounced among participants with SLDs.

The correlational analysis, indeed, highlighted that total CT score was moderately and positively related to IP (visuospatial WM task) among students with and without SLDs. However, the correlation was stronger among students with SDLs. These results corroborated and extended previous knowledge giving us a clue of how WM components are related to chemistry learning in undergraduates with SLDs. Finally, the two linear regression analyses

(one for the TD group and one for the SLDs group) further clarified this relationship. We implemented the same model in both groups, but the interesting results are only among students with SLDs: the model estimated that slow students (those who employed more time to fulfil the CT) are able to successfully perform in the CT when they reach a high score in the visuospatial WM task. In other words, it can be hypothesized that students with SLDs with low competence in the visuospatial WM might struggle more in dealing with chemistry. Providing them with additional time to complete the task may not be sufficient if they lack compensatory tools to support their WM skills.

Chapter 4: Testing the efficacy of different visualisation tools to promote chemistry learning in undergraduates with typically development and with Specific Learning Disabilities (SLDs)

4.1 Study 1: Investigating the differences in students' performance in a chemistry learning task using static pictures vs. dynamic animations among Italian undergrads with typical development

The previous investigations reported in Chapter 3 highlighted that chemistry learning performance is related to students working memory (WM) ability. More precisely, our findings seem to highlight a stronger relationship with visuospatial WM component than with the verbal one. Therefore, objective of this study was to explore whether students' performance in a chemistry learning task differs when learners are exposed to static vs. dynamic representation of the sub-microscopical level. Through the collaboration of many chemistry' professor (Professor Riccardo Bonsignore, Professor Elena Ghibaudi, Professor Enzo Laurenti, Professor Roberto Rabezzana, Professor Alessio Terenzi, Professor Simona Rubino) we engaged a wide sample of undergraduate students. Students were assessed during these professors' classes.

Firstly, we observed how the students performed in a chemistry learning task when sub-microscopical level is presented throughout static or dynamic images. Finally, we investigated the relationship between students' performance in the two different conditions (static vs. dynamic) and WM components (verbal and visuospatial).

Methods

Procedure

The present study protocol is part of the research project "Exploratory investigation of the cognitive processes involved in learning chemistry" submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023). The established design consists of two sessions, which were administered separately: one for the assessment of chemistry learning ability and an additional session for the assessment of the domain-general cognitive abilities. The data collection was implemented between October and December 2024. These two phases were structured as follows:

- *Assessment of chemistry learning abilities*
  It lasted approximately one hour, and it was carried out during a collective session. Students were asked to perform a chemistry task (described below), and to fulfil a short questionnaire asking them few personal details (age, gender, and type of degree course). The chemistry learning task could be assessed in static vs. dynamic condition based on the type of visualisation tool implemented. Each class has been randomly assigned to one of the two conditions.
- *Assessment of domain-general cognitive abilities:*
  This second phase lasted approximately one hour, and it was carried out during a collective session. Students were assessed using two WM tasks (a verbal and a visuospatial one), and the Cattell's Fluid Intelligence Test, Scale 2 (Weiß, 2006) that gives us an estimation of their IQ (Intelligence Quotient) score. The tasks were implemented using a Learning Management System platform (Moodle). Therefore, all tasks were assessed in person, but students performed them on their own device (smart-phone or tablet or PC).

Participants

The chemistry learning assessment involved 299 undergraduate students with typical development (115 male, 174 females, and 10 prefer not to say/non-binary, M_{age} = 19.28 years, SD_{age} = 1.63 years) enrolled in a scientific-related bachelor's degree course at the University of Palermo (N = 145, 48.5%) and at the University of Turin (N = 154, 51.5%). From this original sample we excluded 7 students that were not enrolled at the first-year. Additionally, we excluded the 10 students that defined themselves as non-binary or "I'd rather not to say".

The final sample included 282 first-year undergraduate students who were assessed with the chemistry learning task (158 static vs. 124 dynamic conditions), and 205 of them completed the cognitive processes assessment too (115 static vs. 90 dynamic conditions). We reported a more detailed description of the sample in the table below (Table 4.1.1).

Table 4.1. 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 assessment (N= 282)	70	88	19.35 (1.46)	Palermo N= 58 (36.7%) Turin N= 100 (63.3%)	42	82	19.08 (1.75)	Palermo N= 77 (62.1%) Turin N= 47 (37.9%)
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%)

All the 282 students were enrolled in a scientific degree course that included at least a general chemistry exam in its curriculum: Agro-engeneering (9, static); Biotechnology (49, static); Chemistry (37, dynamic); Pharmacy (40, dynamic); Biology (67, static); Natural Science (33 in the static and 47 in the dynamic). When we narrowed the attention on the 205 who took part to the cognitive processes assessment, the number of the students was: 7 for Agro-engeneering (static); 29 for Biotechnology (static); 28 for Chemistry (dynamic); 28 for Pharmacy (dynamic); 60 for Biology (static); 33 and 19 for Natural Science (static and dynamic respectively).

Instruments

Chemistry Task (CT)

The CT was designed ad hoc for the present research, and its structure resembled the Learning Task included in the Italian battery for the assessment of study method among undergraduates (De Beni et al., 2014). The CT assesses students' chemistry learning ability: students watch a recorded video-class about liquid crystals, and after that they answer a short final test (10 multi-choice questions – 5 textual and 5 visual), and it was administered online using Qualtrics platform. A detailed description of the task is reported in the Instrument section of Study 1 in the chapter 3 (pp. 62-68). The main differences in this new investigation were the following: the video-class had been assessed in two conditions (static vs. dynamic); we removed the teacher's frame, so they could only hear the explanation without seeing who was talking.

In the static condition students assisted the video-class where the liquid crystal's structures were presented as static pictures, and the same pictures were reported in the slides. On the other hand, in the dynamic video-class the crystal's structures were presented as animations (rotating 360° around the vertical axis). The slides that students used to follow the video-class and to review the topic did not include the animation, and the structures were presented simply as pictures.

In both conditions the final score was calculated as the sum of correct answers (maximum score = 10), and the missing answers were counted as errors. The number of correct textual and visual responses was also determined separately (maximum score = 5 for both cases). The number of correct factual (maximum score = 4) and conceptual (maximum score = 6) questions was calculated too, and their score was transformed into percentage so the two measures could be compared (see below).

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

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

Verbal Working Memory (WM) tasks

The Listening Span Task – LST (De Beni et al., 2008) was implemented to assess students' verbal WM. Students listened to and were asked to decide the truthfulness of a series of statements (from two sentences up to six), and after each set of sentences they had to recall the last word of each statement. A detailed description of this task is given in the Instrument section in Study 1 of chapter 3 (p. 68).

This task assesses students' ability to maintain and manipulate (update) verbal information. The final score was obtained summing up the number of words recalled in the proper order of presentation (maximum score = 20). According to the manual (De Beni et al., 2008) the split-half correlation is $r = .87$.

Visuospatial Working Memory (WM) tasks

Imaginative Puzzle – IP (De Beni et al., 2008; Richardson & Vecchi, 2002) evaluated students' visuospatial WM. This task consisted of 27 items organized in nine levels (from level 2 to level 10, with three tasks per level). Students must mentally reassemble a picture of a familiar object shattered in multiple pieces. A detailed definition of this task is reported in the Instrument section of Study 1 in chapter 3 (pp. 68-69).

The final score was measured summing up the level-number of the most three complex levels successfully completed by the student (maximum score = 30). The maximum score in this task is 30. According to the manual (De Beni et al., 2008) the Cronbach alpha is $\alpha = .83$.

Estimated Intelligence Quotient (Estimated IQ)

Cattell's Fluid Intelligence Scale (Weiß, 2006) allowed us to have an estimated Intelligent Quotient (IQ) of the students who took part in the investigation. The manual included two different scales (part 1 and part 2) and in this context we used only Part 2. We adopted the conversion tables within the manual to calculate an estimated IQ score. The assessment consisted of four different types of problems, and students were asked to solve as many problems as possible for each set in a limited-time period. The typology of problems are *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). For a better explanation of each type of problem see Study 2 in chapter 3 (pp. 77-78).

The final score was obtained counting the number of right answers (maximum score =45), and it was transformed into the estimated IQ score, according to the normative tables included in the manual. Overall, the internal consistency of the current sample was Cronbach's $\alpha = .56$.

Data Analysis

First, we analysed and compared students' performance in the CT in the two conditions (static vs. dynamic). We calculated the descriptives (mean and standard deviation) of the total score and the partial scores (textual and visual as well as factual and conceptual questions). Additionally, we explored further this comparison. Given the non-normality of the data (indicated by a significant Shapiro-Wilk test) we implemented the non-parametric alternatives tests to the Student's t-test.

Second, we measured descriptive statistics of the students' performance in the cognitive tasks (LST, IP, and estimated IQ). We explored the relationship between CT and cognitive tasks performance (N = 205 students; 115 in the static and 90 in the dynamic condition) implementing a correlation analysis. Finally, we decided to examine in depth whether there were some differences between static and dynamic conditions performance based on students' visuospatial WM ability. Consequently, we divided the 205 students in three groups, according to their performance at the IP task (low: IP ≤ 20; medium: 21 ≥ IP ≥ 26; high: IP ≥ 27) and we computed two separate (one for the static and one for the dynamic conditions) one-way non-parametric ANOVAs (Kruskal-Wallis) and we compared how differently these three groups performed in the textual and visual questions. The same comparison was made for the factual and the conceptual questions. In this last investigation we compared the percentage of accuracy because the factual questions are 4, whereas the conceptual ones are 6.

Finally, we considered the two groups (static vs. dynamic condition) together and we computed a step-wise regression analysis using the Total score at the Chemistry Task as dependent variable and the cognitive tasks as well as the type of condition (static vs. dynamic) as predictors. The interaction IP score*condition and Estimated IQ score*condition were also included in the model to deeply understand whether the visuospatial WM and the general cognitive ability are differently involved in the dynamic condition.

Data analysis was computed with the Jamovi Project Version 2.3 (2022) and R Studio (2023).

Results

Students' performance at the chemistry task (CT): static vs. dynamic condition

Firstly, descriptive statistics (mean and standard deviation) have been calculated. Students' Total score and partial scores (textual vs. visual; factual vs. conceptual) at the CT as well as the time to fulfil the final test (Time) were examined and they were reported in Table 4.1.2.

Table 4.1.2 Mean (M) and standard deviation (SD) for the accuracy (number of correct answers) in the CT as well as the time for the static and dynamic conditions.

	Static			Dynamic		
	M	*SD*	*Median*	*M*	*SD*	*Median*
Total score	5.96	1.86	6	5.65	1.93	6
Textual score	3.45	1.03	3	3.31	1.15	3
Visual score	2.51	1.30	2.5	2.35	1.29	2
Factual score	69.15%	24.79%	75%	66.33%	25.91%	75%
Conceptual score	53.27%	21.81%	50%	50.00%	22.89%	50%
Time (in seconds)	463	123	441	473	114	472.5

The descriptive statistics reported in Table 4.1.2 show that the accuracy and time were similar in static and dynamic conditions. Six separated non-parametric independent sample t-tests were computed, and the findings confirm that there is no significant difference in students' performance in the two conditions. The Mann-Whitney U were not significant: total score U = 9004, p = .238; verbal score U = 9287, p = .436; visual score U = 9070, p = .272; factual score U = 9133, p = .350; conceptual score U = 9017, p = .240; time U = 9075, p =. 289.

Overall, this first investigation seems to point out that students perform similarly in the two conditions. Hence, the introduction of dynamic representation does not appear to improve students' understanding as well as it does not enhance students' ability to deal with sub-microscopical level of reality.

The sample comprised two parallel first-year courses (A and B) within the same program, Natural Science degree. We considered it might be of interest to restrict our analysis to a sub-sample of students enrolled in the same program at the same university, to examine whether this more comparable group could provide further insights. The two groups were randomly assigned, by coin toss, to either the static or dynamic condition. Unfortunately, given the absence of further significant results, we chose to report this exploratory analysis in the Appendix 2 (p. 183).

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

The results we observed could be better understood taking into consideration the individual differences in the cognitive processes. Therefore, we focused the attention on the 205 students that were assessed both with CT and the cognitive tasks. Descriptive statistics (mean and standard deviation) had been computed and were reported in Table 4.1.3.

Table 4.1.3 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*
Cognitive tasks	LST – verbal WM	17.0	2.61	17	15.9	3.20	16.50	4130*	.012
	IP – visual WM	24.0	3.62	25	22.5	4.10	22	4025**	.006
	Estimated IQ score	109.3	12.95	111	103.2	13.01	103	3842**	.002
Chemistry task (CT)	Total	5.99	1.90	6	5.94	1.86	6	5147	.947
	Textual	3.51	1.05	4	3.46	1.12	4	5106	.866
	Visual	2.48	1.33	2	2.49	1.27	2	5157	.965
	Factual	70.43%	25.34%	75%	69.17%	23.72%	75%	4935	.549
	Conceptual	52.90%	21.99%	50%	52.96%	22.84%	50%	5122	.898
	Time (in seconds)	454	110	439	458	106	450	4976	.638

Note. * p< .05; ** p< .01.

These findings stimulated an interesting thought: the two groups were significantly different in terms of cognitive processes performance. More precisely, in the three cognitive tasks the dynamic group performed significantly worse compared to the static one. Despite the inferior scores in these tasks (that we have previously demonstrated to be related to CT performance – see Chapter 3) this group did not achieve lower scores in the CT, compared to the static group. Additionally, we computed two separated correlational analyses (one for the static and one for the dynamic group) and the results confirm that in the dynamic group students' performance in the CT was less related to their achievements in the cognitive tasks (see Table 4.1.4).

Table 4.1.4 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)	.07	1			.11	1		
3.Estimated IQ	-.06	.44***	1		.13	.41***	1	
4. CT (Total score)	.16	.49***	.27**	1	.27**	.21	.42***	1

Note. * p< .05; ** p< .010; *** p< .001.

Note. LST = Listening Span Test (Verbal WM task); IP = Imaginative Puzzle (Visuospatial WM task); Estimated IQ = estimation of intelligence quotient; CT = Chemistry Task.

The results showed that in the static group the total score at the CT is significantly related to IP task measuring visuospatial WM (correlation is moderate and positive) and to the estimated IQ (correlation is low and positive). On the other hand, it can be noticed that in the dynamic group students' performance in the CT was significantly related to the LST task measuring verbal WM (correlation is low and positive) and to the estimated IQ score (correlation is moderate and positive). These results highlighted that dealing with dynamic representations loads up on general cognitive ability, but it was not significantly related to visuospatial WM abilities.

Additionally, we further examined whether there were some differences between static and dynamic groups' performance in the partial scores based on students' visuospatial WM ability.

We divided the 205 students in three groups, according to their performance at the IP task (low: IP ≤ 20; medium: 21 ≥ IP ≥ 26; high: IP ≥ 27) and we computed four separate (two for the static and two for the dynamic condition) one-way non-parametric ANOVAs (Kruskal-Wallis) comparing how these three groups performed in the textual and visual questions. The same comparison was made for the factual and the conceptual questions. In this last investigation we compared the percentage of accuracy because the factual questions are 4, whereas the conceptual ones are 6.

Table 4.1.5 Results of the-way non-parametric ANOVAs (Kruskal-Wallis) comparing the three groups' performances in the total and 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	.89	3.44	1.06	3.92	1.03	**6.53****	.004
Visual	1.85	1.26	2.31	1.25	3.19	1.19	**6.93****	.003
Factual	60.19%	25.25%	71.63%	25.74%	76.39%	23.10%	3.23	.051
Conceptual	42.59%	19.79%	48.08%	19.71%	67.59%	19.50%	**11.1*****	<.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	.119
Visual	2.32	1.20	2.26	1.19	3.09	1.38	3.05	.067
Factual	63.97%	22.35%	67.65%	25.25%	79.55%	21.32%	**6.86****	.003
Conceptual	50.98%	20.08%	49.02%	23.19%	62.12%	24.76%	2.32	.114

Note. * p< .05; ** p< .010; *** p< .001.

Note. IP = Imaginative Puzzle (Visuospatial WM task)

The analyses pointed out a significant effect of the Imaginative Puzzle (IP) group. In particular, in the static group there was a significant difference between IP groups 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, in the dynamic group a significant difference was observed between the IP groups for the factual questions only (Low IP^{a} < Medium IP^{a,b} < High IP^{b}). In other words, the data showed that people with high score in the visuospatial WM task tend to perform better in the chemistry task when they are exposed to the static condition. Whereas this is less evident in the dynamic condition, where the only difference emergers in the factual questions.

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

Finally, we implemented a step-wise regression analysis using the Total score at the Chemistry Task as a dependent variable and the cognitive tasks as well as the type of condition (static vs. dynamic) as predictors. Given the results of the correlational analyses the interactions IP score*condition and Estimated IQ score*condition were also included in the model. The results are reported in Table 4.1.6 and the interactions in Figure 4.1.1.

Table 4.1.6 Results of the regression analysis comparing the three groups' performances in the total and partial scores 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	<.001
LST – verbal WM	**0.088**	**0.042**	**0.01**	**0.17**	**2.12***	**.035**
IP – visual WM	-0.006	0.049	-0.58	-0.10	0.09	.901
Estimated IQ score	**0.054**	**0.015**	**0.02**	**0.08**	**3.48*****	**<.001**
Group (Static vs. Dynamic)	-0.419	0.249	-0.91	0.07	-1.68	.094
IP*Group	**0.212**	**0.069**	**0.07**	**0.35**	**3.06****	**.003**
Estimated IQ*Group	-0.034	0.021	-0.08	0.01	-1.64	.104

$R^2adj = 0.1895$, $F(6, 198) = 8.949$, $p < 0.001$

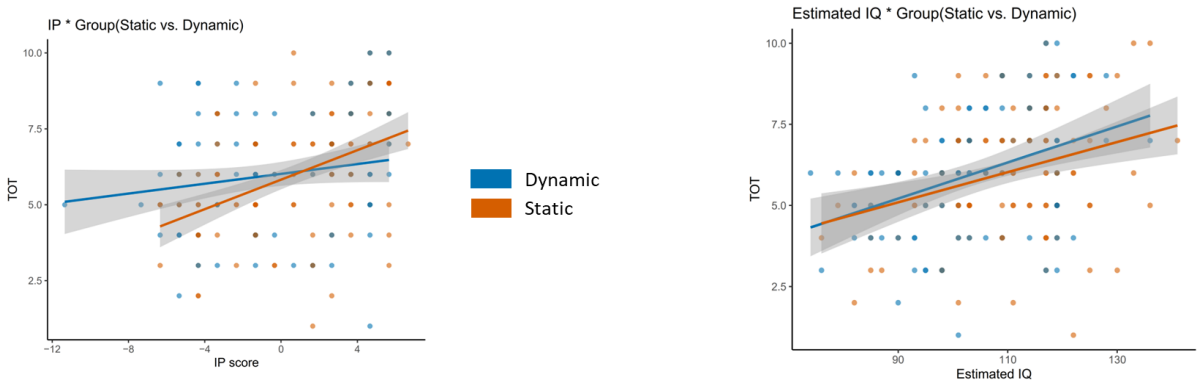


Figure 4.1.1 Interaction plots: on the right we can observe the interaction between the IP score and the condition (static vs. dynamic); whereas on the left side is reported the not significant interaction between Estimated IQ and condition.

The regression analysis showed that both verbal WM and the estimated IQ score were significant predictors, while the visuospatial WM seemed not significant. On the other hand, it emerged a significant relationship between the visuospatial WM and the condition: low IP score is associated with lower performance in the Chemistry Task only in the static condition.

Discussion

In this first study we aimed to investigate students' performance in a chemistry learning task when they were exposed to different types of visualisation tools (static pictures vs. dynamic animations). Therefore, we assessed a wide sample of Italian undergraduates with a chemistry learning task in two different conditions (static vs. dynamic). In accordance with our previous research (see Chapter 3) we additionally explored how students' performance in the chemistry learning tasks was related to WM components (verbal and visuospatial) and general cognitive ability.

Firstly, we compared students' performance in static vs. dynamic conditions among the overall sample. We observed that the two groups performed likewise, and no significant difference was observed. The existing literature concerning the implementation of dynamic visualisation tools presents conflicting evidence. According to a recent meta-analysis (Castro-Alonso, Wong, et al., 2019) it can be concluded that dynamic representation can have positive effects on science (chemistry included) learning, but this effect is higher when the sample includes more male than females. Other authors (e.g., Castro-Alonso et al., 2015) stated that coping with dynamic visualisations (such as video, animations or augmented reality) could be complex from a cognitive point of view, since this material could be too fleeting and difficult to follow. Furthermore, students could self-perceive a high cognitive load when they deal with these materials as Peeters et al. (2023) demonstrated. The authors tested the efficacy of using Augmented Reality (AR) to promote students' understanding of chemical phenomena related to the sub-microscopical level among secondary school students. They observed no significant

difference between the group that used the AR and the no-AR group in terms of learning performance; whereas they detected that the AR group self-perceived higher level of cognitive load compared to the no-AR one.

Recently, an insightful reflection, that considered the implementation of the visualization tools within the framework of Cognitive Load Theory, emphasizing that the design of effective instruments should be grounded in its core principles (Castro-Alonso, Ayres, et al., 2019). Therefore, to grasp a more complete understanding of the beneficial aspects of introducing dynamic representation it is necessary to extend and include in our framework the cognitive aspects. More precisely, we assessed students' WM (both verbal and visuospatial components), and general cognitive ability (estimated intelligence quotient – IQ). This further investigation focused the attention on the sub-sample of 205 students who completed both chemistry learning and cognitive assessment. This analysis revealed that the two groups (static vs. dynamic condition) were significatively different in terms of cognitive abilities: the dynamic group performed significantly worse in all the three tasks. Nevertheless, the two groups did not perform differently in the chemistry learning task.

The correlational analysis between students' accuracy in the chemistry learning task and in the cognitive tasks revealed that the estimated IQ is significantly related to chemistry learning, and the relationship is stronger in the dynamic group. This result was consistent with current literature (Castro-Alonso, Ayres, et al., 2019; 2015; Peeters et al., 2023) which acknowledges that higher cognitive load is associated with dynamic visualisations compared to the static ones. Moreover, the analysis pointed out that chemistry learning task performance was moderately related to 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 confirmed what is well established in literature (e.g., Hodgkiss et al., 2018; Rhodes et al., 2016; St Clair-Thompson & Gathercole, 2006): that visuospatial WM components are related to students' accuracy in a chemistry learning task. More precisely, this finding was coherent with our previous results presented in Chapter 3. On the other hand, the correlational results in the dynamic group highlight that students' accuracy was weakly and non-significantly related to visuospatial WM, and it was weakly related to verbal WM. This pattern may be partially related to the nature visuospatial WM task (De Beni et al., 2008; Richardson & Vecchi, 2002) employed, that requires active manipulation of static visuospatial information. Given that students in the dynamic condition were asked to process animated visualizations of sub-microscopic representations, the chosen task did not capture this dynamic aspect of visual processing. However, these results, together with those observed for estimated IQ, seemed to suggest that students in the dynamic group have to deal with complex visual information as well as with verbal one, and this placed a greater load up on their verbal WM compared to the static group. However, due to the complexity of the task, the learning outcomes in the dynamic condition were more related to students' general cognitive abilities, rather than on to WM components.

The non-parametric ANOVAs that we implemented pointed out that the differences between the three groups (low, medium and high visuospatial working memory performance) could be observed primarily in the static group. Whereas the three groups perform likewise in

the dynamic condition. This final result suggested that dynamic animations could be a valuable resource to promote chemistry learning among students with low visuospatial WM ability. We observed a significant difference only in the factual scores. Hence, students performed better when their visuospatial WM ability was high, probably because they were better able to manage complex materials and, consequently, experienced lower cognitive load compared to students with low visuospatial WM capacity. This advantage was reflected in their higher accuracy on factual questions requiring the recall of either verbal or visual information.

Finally, to better understand whether the cognitive aspects (verbal WM, visuospatial WM and estimated IQ score) were differently related to Chemistry Task performance in the two conditions (static vs. dynamic) we implemented a step-wise regression analysis considering the whole sample. The results were consistent with those observed in the correlation analyses and in the non-parametric ANOVAs: it emerged that both in static and dynamic conditions students with higher verbal WM scores perform better; likewise students with higher estimated IQ scores performed better in both conditions. We hypothesize that the verbal WM and estimated IQ score, differently from previous studies (see Chapter 3), were significant predictors because in this new assessment we had removed the professor' frame, and students could only hear the explanation without seeing who was talking. Therefore, their verbal WM was more loaded than previous investigation, since they had to rely more on their verbal processing abilities. Furthermore, the interaction effect (IP score*condition) confirmed that the introduction of dynamic animations could support students with low visuospatial WM ability in understanding a chemistry topic that asks to deal with sub-microscopic level of reality. On the other hand, the interaction Estimated IQ*condition resulted not significant, even if looking at the plots we could observe that the relationship between general cognitive ability and chemistry task performance seemed to be slightly stronger in the dynamic group. Overall, this final analysis confirmed that dealing with dynamic animation loaded on general cognitive ability (Castro-Alonso, Ayres, et al., 2019; 2015; Peeters et al., 2023), but it suggested that they can represent a supporting tool for students with lower visuospatial WM skills.

4.2 Study 2 - Static pictures vs. dynamic animations among Italian undergrads with Specific Learning Disabilities (SLDs)

This second study focused on students with Specific Learning Disabilities (SLDs). The primary objective of this study was to investigate whether the introduction of dynamic animations may affect understanding among students with SLDs. Thanks to the collaboration of Professor Roberta Cavaglià, Professor Riccardo Bonsignore, Professor Elena Ghibaudi, Professor Enzo Laurenti, Professor Roberto Rabezzana, Professor Alessio Terenzi, Professor Simona Rubino, and Professor Barbara Sini, we were able to engage 30 undergraduate students with SLDs. They have been assessed with the same chemistry task employed in Study 1 (section 4.1): 15 students were assigned to the static condition, and 15 to the dynamic condition. The 67% of them (20 students, 10 per each condition) also completed the cognitive processes assessment. They were paired with a group of students with typical development matched for gender, estimated IQ, and both verbal and visuospatial working memory. Hence, we investigated whether the two groups performed differently in the static vs. dynamic condition.

Methods

Procedure

The present investigation was part of the research project "Exploratory investigation of the cognitive processes involved in learning chemistry" that was submitted to and accepted by the Bioethical Board of the University of Turin (protocol nr. 0059554, date 30/01/2023). The assessment was implemented between October 2024 and April 2025, and likewise previous investigations it concerns two phases, which were administered separately:

- *Assessment of chemistry learning abilities:*
  This first phase lasted approximately 1 hour, and students were asked to perform a chemistry learning task (described below), and to fulfil a short questionnaire asking them few personal details (age, gender, and type of degree course). The chemistry learning task has been administered in two different conditions: static vs. dynamic conditions. Students were randomly assigned to one of the two conditions.

- *Assessment of WM and visuospatial abilities:*
  This second assessment lasted approximately 1 hour, and students were asked to perform two WM tasks (a verbal and a visuospatial WM task). Additionally, students' estimated IQ (Intelligence Quotient) was measured using the Cattell's Fluid Intelligence Test, Scale 2 (Weiß, 2006). The 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.

This procedure and methodology are similar to those used in the previous investigation with students with typical development (Study 1, Chapter 4). The assessment in both phases was carried out in a collective session.

Participants

The first phase (chemistry learning assessment) involved 30 undergraduate Italian students (M_{age} = 21.2 years, *SD* = 4.31) with Specific Learning Disabilities (SLDs), who were enrolled at the University of Turin (*N* = 23; 77%), and the University of Palermo (*N* = 7; 23%). The sample included 14 females (47%), and 16 males (53%). All these students possessed a certified clinical diagnosis of SLDs. According to the Italian legal criteria for SLDs (Law 170, 2010) and the Italian National Guidelines for SLDs (Istituto Superiore di Sanità [Italian National Institute of Health], 2022), the main criteria used for the diagnosis of SLD are: (i) academic achievement in specific areas (reading, writing, and/or arithmetic) below the 5th percentile, or more than 2 SD below average, when assessed using relevant standardized tests; (ii) students' difficulties are not due to sociocultural, educational, emotional, intellectual, sensory, or neurological problems; and (iii) these specific impairments are persistent and are not due to environmental factors such as sociocultural disadvantage, lack of proficiency in the language or inadequate school education; and emotional factors like for example emotional deprivation or affective problems within the family context.

In the present sample 36% of students had difficulties in reading and/or writing, the 25% have difficulties in mathematics, and the 39% had difficulties both in reading and/or writing and in mathematics. Students were all enrolled in different scientific-related bachelor's degree courses such as: Agricultural sciences; Biology; Biotechnology; Chemistry; Natural sciences; Artificial Intelligence and biomedicine.

A sub-sample of 20 students (M_{age} = 20.5 years, *SD* = 2.21; 55% female) took part in the second assessment phase. The 30% of the sub-sample had difficulties in reading and/or writing (3 students in the static and 3 in the dynamic condition), the 35% had difficulties in mathematics (3 students in the static and 4 in the dynamic condition), and the 35% had difficulties both in reading and/or writing and in mathematic (4 students in the static and 3 in the dynamic condition). We reported a more detailed description of the sample and sub-sample in the table below (Table 4.2.1).

Table 4.2.1 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 assessment (N= 15)	8	7	21.6 (4.73)	Palermo N= 3 (20%) Turin N= 12 (80%)	8	7	20.8 (4.00)	Palermo N= 4 (27%) Turin N= 11 (73%)
Chemistry learning and cognitive processes assessment (N= 10)	4	6	20.9 (2.51)	Palermo N= 1 (10%) Turin N= 9 (90%)	5	5	20.1 (1.91)	Palermo N= 2 (20%) Turin N= 8 (80%)

Instruments

Chemistry Task (CT)

The CT was designed *ad hoc* for the present research, and its structure resembles the Learning Task included in the Italian battery for the assessment of study method among undergraduates (De Beni et al., 2014). The task assesses students' chemistry learning ability: students watch a recorded video-class about liquid crystals, and after that they answer a short final test (10 multi-choice questions – 5 textual and 5 visual), and it was administered online using Qualtrics platform. A detailed description of the task is reported in the Instrument section of Study 1 of chapter 3 and 4 (pp. 62-68 and pp. 106-107, respectively).

Listening Span Task (LST) – Verbal WM

Verbal WM was assessed using the Italian version of the Listening Span Task – LST (De Beni et al., 2008). For a comprehensive overview of this task, please refer to the Instrument section of Study 1 in this chapter (p. 68).

This task measured students' ability to maintain and manipulate (update) verbal information. The final score was obtained summing up the number of words recalled in the propter order of presentation (maximum score = 20).

Imaginative Puzzle (IP) - Visuospatial WM

Imaginative Puzzle – IP (De Beni et al., 2008; Richardson & Vecchi, 2002) was administered to assess students' visuospatial WM. Chapter 3 contains a detailed description of this task in the Instrument section of Study 1 (pp. 68-69).

The final score was measured summing up the level-number of the most three complex levels successfully completed by the student (maximum score = 30).

Estimated Intelligence Quotient (Estimated IQ)

In the present investigation we measured students' estimated Intelligent Quotient (IQ) score administering the Cattell's Fluid Intelligence Scale (Weiß, 2006). For a comprehensive account of this assignment, please refer to the Instrument section of Study 1 in this chapter (pp. 77-78), and an example of each type of problem is reported in Figure 3.2.2 (p. 78).

Data Analysis

First, descriptive statistics (mean and standard deviation) of each variable of the chemistry task (CT) were computed among the 30 students with SLDs. We analysed and compared students' performance in the CT in the two conditions (static vs. dynamic). Total score, partial scores (textual and visual as well as factual and conceptual questions) as well as the time employed to fulfil the final test were observed. Previous investigations have demonstrated that the data do not have a normal distribution, hence we compared the two groups using a non-parametric alternative to the independent sample t-tests.

Additionally, we narrowed down the attention on the sub-sample of students with SLDs that completed the cognitive assessment. We compared whether the two groups perform differently in the chemistry task.

Finally, we paired the students with SLDs with a group of students with typical development matched for gender, estimated IQ, and both verbal and visuospatial WM. We investigated whether the two groups perform differently in the static vs. dynamic condition. Prior research has shown that the data deviate from a normal distribution, consequently a non-parametric alternative to the independent sample t-tests was utilised for the purpose of comparing the two groups.

Data analysis was computed with the Jamovi Project Version 2.3 (2022).

Results

Students with SLDs and CT performance: static vs. dynamic visual tools

Descriptive statistics (mean and standard deviation) had been calculated. Students' total score and partial scores (textual vs. visual; factual vs. conceptual) at the CT as well as the time to fulfil the final test (Time) were examined and they were reported in Table 4.2.2.

Table 4.2.2 Mean (M) and standard deviation (SD) for the accuracy (number of correct answers) in the CT as well as the time for the static and dynamic conditions.

	Static (*N*= 15)			Dynamic (*N*= 15)		
	M	*SD*	*Median*	*M*	*SD*	*Median*
Total score	4.87	1.96	5	4.27	1.87	4
Textual score	2.80	1.08	3	2.53	1.19	3
Visual score	2.07	1.44	2	1.73	1.03	2
Factual score	51.67%	27.49%	50%	55.00%	25.35%	50%
Conceptual score	46.67%	22.89%	50%	34.44%	19.38%	33.33%
Time (in seconds)	489	168	473	503	117	522

The descriptive statistics showed that the accuracy and time were similar in static and dynamic conditions. We statistically tested this difference using six separated non-parametric independent sample t-tests. We implemented the non-parametric tests because the assumption of normality was violated. The Mann-Whitney U were not significant: total score $U = 96.0$, $p = .499$; verbal score $U = 98.5$, $p = .559$; visual score $U = 101.0$, $p = .633$; factual score $U = 104.5$, $p = .745$; conceptual score $U = 79.0$, $p = .157$; time $U = 92.5$, $p = .419$.

Overall, these findings confirm that there was no significant difference in students' performance in the two conditions, and the findings replicated those observed among students with typical development (Study 1 of the present chapter).

Students' performance at the chemistry task (CT) in static vs. dynamic conditions: exploring the individual cognitive processes involved in students with SLDs

The results could be better understood considering the individual differences, in terms of cognitive processes. Therefore, we focused the attention on the 20 students that were assessed both with CT and the cognitive tasks. Descriptive statistics (mean and standard deviation) were computed and were reported in Table 4.2.3.

Table 4.2. 3 Mean (M), standard deviation (SD), and non-parametric comparisons of the performances of students with SLDs in the two conditions (static vs. dynamic)

		Static (N=10)		Dynamic (N= 10)		Non-parametric comparisons	
		M	*SD*	*M*	*SD*	*Mann-Whitney's U*	*p-value*
Cognitive tasks	LST – verbal WM	13.3	3.80	11.9	4.08	36.5	.511
	IP – visual WM	21.7	3.83	23.4	3.89	35.5	.288
	Estimated IQ score	96.6	12.17	101.2	13.33	38.5	.403
Chemistry task (CT)	Total	5.20	1.93	3.90	1.73	32.0	.178
	Textual	3.10	0.88	2.40	1.17	32.5	.172
	Visual	2.10	1.29	1.50	0.85	38.0	.357
	Factual	57.50%	23.72%	47.50%	24.86%	40.5	.474
	Conceptual	48.33%	25.40%	33.33%	15.71%	31.0	.148
	Time (in seconds)	522	180	490	119	50.0	1.000

The sub-sample of students with SLDs included 10 students exposed to the static condition and 10 students assessed in the dynamic one. The two groups are likewise in terms of cognitive processes performance as well as in terms of chemistry task performance.

Finally, we compared their performance with a group of students with typical development matched for gender, estimated IQ, and both verbal and visuospatial working memory. Both for the static and the dynamic condition the students with and without SLDs were comparable (see Table 4.2.4).

Table 4.2.4 Mean (M) and standard deviation (SD) in the cognitive tasks: comparing profiles of students with and without SLDs

	SLDs (N=10)		TD (N= 10)		*Mann-Whitney's U*	*p-value*
	M	*SD*	*M*	*SD*		
Static						
LST – verbal WM	13.3	3.80	15.8	2.39	29.0	.116
IP – visual WM	21.7	3.83	21.5	3.69	48.0	.909
Estimated IQ score	96.6	12.17	95.4	13.88	47.5	.879
	SLDs (N=10)		TD (N= 10)			
Dynamic						
LST – verbal WM	11.9	4.08	14.3	4.32	30.5	.251
IP – visual WM	23.4	3.89	23.6	3.95	49.0	.970
Estimated IQ score	101.2	13.33	99.3	13.85	45.5	.761

Note. LST = Listening Span Test (verbal WM task); IP = Imaginative Puzzle (Visuospatial WM task)

Finally, we compared how the paired group performed in the static vs. dynamic condition, observing whether the students with SLDs performed differently from their pair with typical development (TD). The results were reported in Table 4.2.5.

Table 4.2.5 Mean (M),standard deviation (SD) and median in the chemistry tasks: comparing performances of students with and without SLDs

	SLDs (N=10)			TD (N= 10)			*Mann-Whitney's U*	*p-value*
	M	*SD*	*Median*	*M*	*SD*	*Median*		
Static								
Total score	5.20	1.93	5	5.80	1.87	6	38.0	.387
Textual	3.10	0.88	3	3.30	0.95	3	46.5	.806
Visual	2.10	1.29	2	2.50	1.18	2.5	36.0	.291
Factual	57.50%	23.72%	50%	65.00%	24.15%	75%	39.5	.422
Conceptual	48.33%	25.40%	50%	53.33%	20.49%	50%	43.5	.637
Time (seconds)	522	180	485.5	402	99	397	29.0	.123
	SLDs (N=10)			TD (N= 10)				
Dynamic								
Total score	3.90	1.73	3.5	5.90	1.73	6	**22.0***	**.033**
Textual	2.40	1.17	2.5	3.30	1.16	3.5	29.0	.109
Visual	1.50	0.85	1.5	2.60	0.97	2	**19.5***	**.015**
Factual	47.50%	24.86%	50%	70.00%	22.97%	62.5%	28.0	.085
Conceptual	33.33%	15.71%	33.33%	51.67%	22.84%	50%	27.0	.076
Time (seconds)	490	119	513.5	481	107	479.5	44.5	.705

Note. * p< .05; ** p< .010; *** p< .001;

The analyses pointed out that in the static condition the students' performance was not significantly different from their pair with TD. On the other hand, when we replicated the same analyses on the group of students with SLDs exposed to the dynamic condition, we observed that they performed significantly worse compared to their pair with TD in the total score as well as in the visual score.

Discussion

This second study aimed to investigate whether the implementation of static pictures vs. dynamic animations differently affected the performance in a chemistry learning task in students with SLDs. Therefore, we assessed a sample of students with SLDs with a chemistry learning task in two different conditions (static vs. dynamic). Additionally, in order to better

understand how the students' performance was related to cognitive processes they have been also assessed with two WM tasks (measuring verbal and visuospatial components) and a general cognitive ability task.

Firstly, we compared students' performance in static vs. dynamic conditions among the whole sample (N= 30 students). The results replicated what we have observed in study 1 (present chapter) with students with TD: two groups performed likewise, and no significant difference was observed among students with SLDs in static vs. dynamic conditions. However, looking at descriptives (average scores) it emerged that scores of the dynamic group were slightly lower and the time to fulfil the task was more compared to the static group. We hypothesized that this may be attributed to the higher cognitive load associated with processing dynamic animation, that has already been demonstrated (Castro-Alonso et al., 2015; Peeters et al., 2023). Coping with dynamic visualisations (such as video, animations or augmented reality) could be complex from a cognitive point of view, due to their fleeting nature (Castro-Alonso et al., 2015). Furthermore, Peeters et al. (2023) observed that students self-perceive a higher cognitive load when they deal with complex visualisation tools (such as Augmented Reality) compared to peers exposed to static pictures. However, none of these investigations specifically targeted students with SLDs. There are some studies among younger students demonstrating that the implementation of video-based mathematics instruction to solve a problem can improve students problem-solving performance (Kellems et al., 2020). Similar results were observed using video modelling to teach geometry problems (Satsangi et al., 2020) or mathematics (Morris et al., 2022). However, less is known about university students with SLDs. Therefore, we narrowed down the investigation on a sub-sample of 20 students with SLDs (10 static and 10 dynamic conditions) who took part in the cognitive assessment too. The two groups presented comparable cognitive profiles (similar scores in the verbal and visuospatial WM tasks, and similar estimated IQ scores), and their performance in the chemistry task was comparable. However, it could be noted that the scores in the dynamic conditions were slightly lower, suggesting again that the dynamic condition could be more challenging for students with SLDs. To test this hypothesis, we run a final analysis comparing these students' performance in the chemistry task with a matched group of students with TD. The students with and without SLDs had similar performance in the verbal and visuospatial WM tasks, and they had comparable estimated IQ scores. The non-parametric ANOVAs revealed that in the static condition the students with SLDs performed comparably to their peers with TD; on the contrary, in the dynamic condition the former performed significantly worse in the total score and in the visual questions, and in general their accuracy was lower. Overall, these findings seem to lead to the conclusion that the simple introduction of short videos of molecular structures do not automatically improve students with SLDs performance in a chemistry learning task that require them to handle sub-microscopic representations. In literature, studies on students with TD, found that including dynamic animation can promote students' understanding of concepts related to sub-microscopic level in chemistry (Ardac & Akaygun, 2005; Linn et al., 2006; Stieff, 2011), and with study 1 (chapter 4) we have replicated this finding also among a sample of Italian university students with TD. However, there are other valuable contributions that highlighted the complexity of dealing with dynamic animation, especially if students are merely and passively exposed to them (Castro-Alonso, Ayres, et al., 2019). The present findings on

students with SLDs suggested that this is even more true among university students with atypical development. As demonstrated in a recent study (Daniel et al., 2022) investigating adolescents with and without SLDs, they struggle more in perceiving and isolating simple figures/shapes within a complex one and have a poorer performance in a WM task compared to peer with TD. Students with SLDs, indeed, have lower competence in verbal WM (Pizzigallo et al., 2023; Toffalini et al., 2017) and this could represent a significant disadvantage during chemistry learning. We hypothesised that given the higher cognitive load required to process this type of information and the specific weaknesses of students with SLDs, they struggle more than students with typical development in the dynamic condition. Cognitive processing skills of students with SLDs are different compared to their peer with typical development; hence, in the dynamic condition, where they were asked to handle fleeting video showing the molecular structure form different point of view, their WM components were overloaded resulting in a weak performance.

Overall, the results provided valuable and interesting results about the effects of using static vs. dynamic visual tools to explain sub-microscopical chemistry concepts in students with SLDs. These findings could have precious implications in the educational field. They suggest that the simple introduction of dynamic visual tools is not sufficient to promote chemistry understanding among students with SLDs. In other words, teachers and professors have to consider that part of the class will need more time to process this type of information and that their understanding could be supported, reducing the amount of information presented simultaneously within the animations and providing them with verbal explanations that help students in comprehending the video.

Chapter 5: Conclusions

Chemistry students are constantly asked to integrate and interconnect three levels of reality: sub-microscopic, macroscopic and symbolic (Johnson et al., 2010; Johnstone, 1991, 1993). The sub-microscopic level concerns what happens at the particle level (like atoms and molecules) and cannot be directly observed. The macroscopic one refers to what can be directly observed through the senses (such as sight, smell, touch, hearing, and taste). Finally, the symbolic one consists of all the symbols, formulas, and equations that are used in chemical language to describe a chemical phenomenon.

Since the beginning, Johnstone's research (1971) revealed that chemistry students struggle when they have to deal with topics with a heavy information load, such as redox reactions, thermodynamics, moles, organic chemistry, and calculation. In other words, when they have to handle multiple ideas, information, and knowledge at once. This is frequent in this discipline (see Johnstone, 1982) since chemists typically process phenomena at three levels: they observe properties and behaviour (macroscopic); they summarize it using a certain language (symbolic); then they use sub-atomic particles, atoms and molecules to explain the reason behind the directly observable phenomena (sub-microscopic). The lack of fluidity in moving between these three levels of representation is one of the biggest weaknesses among students who are not chemistry experts (Johnstone, 1982). Limited working memory, combined with a lack of chemistry knowledge, adds to these challenges. Expert chemists instead can easily implement strategies organizing multiple elements into a meaningful unit (see for example, Adhikary et al., 2015; Stieff et al., 2020) reducing the overall number of ideas processed simultaneously.

The relationship between chemistry learning and domain-general cognitive processes have been widely explored in literature (Chandran et al., 1987; Hodgkiss et al., 2018; Huang & Liu, 2012; Li et al., 2020; Nedungadi & Shenoy, 2023; Niaz, 1987; Nolte et al., 2024; Overton & Potter, 2011; Pribyl & Bodner, 1987; Rau, 2018; Rhodes et al., 2016; Romero et al., 2024; St Clair-Thompson et al., 2012; Stamovlasis & Papageorgiou, 2012; Stull et al., 2012; Tsaparlis, 2005; Tsaparlis et al., 1998; Upahi et al., 2020; Vilia et al., 2017). However, the complex nature of chemistry, as well as the different aspects that it concerns (Allman et al., 1975) makes the act of systematically synthesising the literature extremely challenging. Multiple investigations have been developed in order to identify the cognitive processes relevant in supporting chemistry learning, pointing out the pivotal role of visuospatial skills and working memory (see for example, Bodner & McMillen, 1986; Hussein & Reid, 2009; Pribyl & Bodner, 1987; St Clair-Thompson et al., 2012; St Clair-Thompson & Gathercole, 2006; Supasorn et al., 2008). The former is mainly associated with students' ability to deal with the sub-microscopic level of reality and the latter with the problem-solving abilities. Therefore, visualization tools (such as physical models, fixed and animated computer models, student-generated drawings or animations, immersive Virtual Realty or Augmented Reality experiences, etc.) can be precious

instruments to promote students understanding of chemical topics, especially when they require dealing with sub-microscopic level. Teachers can obtain positive effects implementing and integrating them with the other activities and providing the students with the proper contextualization. A commonly employed visualization tool involves the integration of dynamic animations into conceptual explanations during a lecture. Such animations can represent an effective pedagogical instrument to facilitate students' comprehension of complex processes operating at both macroscopic and sub-microscopic levels of reality. Overall, it seems that dynamic animations models are the most widely used also among young students (middle school). A meta-analysis (Castro-Alonso, Wong, et al., 2019) has concluded that the use of dynamic visual tools exerts a more positive and effective impact on student learning compared to the static ones. Nevertheless, there are several questions that still remain unresolved and call for further research. For example, how the verbal and visuospatial working memory (WM) components are involved when students are challenged to engage with the sub-microscopic level of reality. Furthermore, another crucial element is that the majority of the studies in literature investigates students with typical development, whereas little is known about students with Specific Learning Disabilities (SLDs) or special needs education. There is no investigation in chemical education that explores whether the introduction of visualization tools can influence academic success among students with learning difficulties. All the literature presented so far focused the attention on typical development students. Further investigations are needed to explore how the implementation of dynamic animations can improve students understanding and dealing with sub-microscopic concepts. Hence, it urges to expand the present literature taking into consideration how the different cognitive processes are related to these students' chemical understanding/learning. More precisely, the existing literature had not adequately explored how the different domain-specific components of WM (verbal and visuospatial) are related to chemistry learning, nor has it explored in depth how students with SLDs acquire chemical knowledge.

The studies presented within the present dissertation attempt to answer to these questions: how verbal and visuospatial components of WM are related to chemistry learning among students with and without SLDs; whether the dynamic visualization of sub-microscopic representation of structures would produce better results in terms of understanding among students with and without SLDs.

The first study was a preparatory investigation involving a small sample (N= 39) of students. The objective of this first study was to assess the adequacy of an *ad hoc* chemistry learning task and an experimental protocol. More precisely, the chemistry task consists of watching a recorded video-class on liquid crystals and filling a multiple-choice final test related to the explained topic. The final test consisted of 10 questions: 5 with text-based response options (Textual) and 5 with picture-based response options (Visual). The whole task had been designed by a multidisciplinary pool of chemistry and psychology experts, and its main goal was to create an ecological tool that measures students' ability to deal with some basic chemical issues (e.g. chirality, molecular and supramolecular structures, isometry, molecular geometry, molecular dynamics, etc.). The qualitative analysis of the chemistry task showed that students performed better in questions asking them to recall information, and they struggled more when

they were required to reach a deep level of understanding of the topic. In other words, their accuracy was lower when the correct response require maintenance and manipulation of information (verbal or visuospatial), as these type of questions are cognitively more challenging and highly burden up on WM resources (Crone et al., 2006). In particular, the students' performance decreases when they are asked to deal with textual or visual material that do not appear directly in the recorded video-class nor in the slides. The correlational analysis, indeed, highlighted that performance in the chemistry task was positively correlated with performance in verbal and visuospatial WM tasks requiring maintenance and manipulation of information.

The second study extended the first investigation, and it provided interesting results proving the different involvement of verbal and visuospatial WM components in explaining undergraduate students' performance in a chemistry task. We used the same chemistry task implemented in study one. The analysis showed that students performed better in the textual questions than in the visual ones. However, this difference was not simply due to a major degree of difficulty of the visual questions, since they were balanced both in terms of degree of comprehension (surface or deep-level of understanding) and type of cognitive processes required (decoding, recalling, inhibition and interference). Additionally, the findings confirmed that students' accuracy was higher in questions that did not employ active manipulation nor complex conceptual issues; whereas students' performance was lower in questions that need a deep-level comprehension of chemical issues. The statistical analysis confirmed that students' percentage of accuracy in the factual questions was significantly higher compared to their accuracy in the conceptual ones. Therefore, students' performance both in textual and visual questions depends on the diverse mobilisation of cognitive abilities, and the most complex questions were those that required integration and manipulation of different information demonstrated by Crone et al. (2006). Furthermore, the correlational analysis pointed out that chemistry tasks scores (total, textual and visual) were moderately and positively correlated to the performance in the visuospatial WM task. Whereas, estimated IQ, verbal WM and Mental Rotation tasks[31] were not related to chemistry task performance. The involvement of visuospatial WM component was further confirmed by the results of a linear regression analysis. This significant involvement of visuospatial WM components was partially explained by the nature of the selected chemistry topic (liquid crystals), which asked the students to deal with chemical concepts that heavily rely on visuospatial abilities (chirality, molecular and supramolecular structures, molecular dynamics, etc.). Our results corroborated previous investigations showing the importance of visuospatial components in chemistry learning (Carter et al., 1987; Duffy et al., 2020; Pribyl & Bodner, 1987; Sorby et al., 2020) and proved that previous findings obtained by Rhodes at al. (2016) among adolescents (visuospatial WM is more involved than verbal WM in chemistry learning) are valid among undergraduates too. Additionally, we implemented further analyses confirming that students with higher visuospatial WM scores performed better in textual and in visual questions than students with

[31] Mental Rotation task: this task assesses the ability to mentally rotate and manipulate 3D objects represented in a 2D. It evaluates visuospatial skills, in particular the Intrinsic-dynamic processes (Uttal et al., 2013).The task can consists of concrete or abstract/geometrical stimuli and it requires the participants to identify, among four alternatives, the two that are a rotated version of the given target.

low visuospatial WM. Finally, comparing the effect-sizes it could be observed that the advantage was more evident in the visual questions. In other words, students, who are not endowed with strong visuospatial WM ability, faced more difficulties in creating and handling mental representations of abstract concepts (such as the visualisation of molecular structures, molecular interactions, chiral centres, molecular symmetry, etc…).

The third and the fourth study were an attempt to extend the investigation to students with SLDs, as numerous investigations (see for example, Carter et al., 1987; Hussein & Reid, 2009; Nedungadi & Shenoy, 2023; Niaz, 1987; Tsaparlis, 2005; Upahi et al., 2020) exploring the relationship between cognitive processes and chemistry learning have primarily involved students with typical development (TD). In the third study we assessed 45 students with SLDs using the same chemistry task used in previous studies (about liquid crystals). They executed the task following the same procedure that has been previously implemented with students with TD. Therefore, students with SLDs were not allowed to benefit from any compensatory or dispensatory tool. Students' performance was assessed in terms of accuracy and time employed to fulfil the final test (consisting of 10 multiple-choice questions). There was no time limit for responding to the questions. It has been widely demonstrated that adults with SLDs are slower in processing and less efficient in manipulate information, especially when these overload verbal WM (Cornoldi et al., 2021; Pizzigallo et al., 2023). Thus, in this case the opportunity to record time could be highly informative, as it can provide valid information about their processing efficiency. The assessment involved also a sample of students with TD, and we compare the two groups performance in the chemistry task. The findings revealed no significant differences between the two groups across most of the scores, with the exception of the textual question score. Moreover, the standard deviations (for each variable) were bigger among students with SLDs than among those with TD, indicating a more heterogeneous performance among students with SLDs compared to those with TD. Overall, this finding confirmed that students with SLDs keep struggling more than students with TD when they have to deal (processing and manipulating) with textual information (Bogdanowicz et al., 2014; Montesano et al., 2020). Furthermore, we focus the attention on the relationship between time employed to execute the test and accuracy. The neurobiological nature of SLDs implies that students' difficulties in reading, writing and/or mathematics persist throughout life; although adults with SLDs may develop compensatory strategies, they still tend to be slower compared to peers with TD (Hatcher et al., 2002; Pizzigallo et al., 2023; Toffalini et al., 2017). The correlation analyses results highlighted that time correlated positively with the total score of the chemistry task both among students with and without SLDs. Nevertheless, the correlation between time and accuracy in the textual and in the visual questions was different for the two groups. Among students with TD, time correlated positively with textual score. By contrast, no correlation between time and visual question scores was found, in this group. In other words, participants who devote more time to the chemistry task tend to perform better on verbal questions, but their accuracy on visual questions does not improve accordingly, suggesting that performance in the latter relied less on time. The opposite pattern was observed for students with SLDs. These students' performance in textual questions did not improve even when they spent more time completing the final test, suggesting that additional time was not sufficient to compensate for their verbal processing difficulties. Conversely, in visual questions, students with SLDs who took more time to respond were more accurate than those who answered quickly, suggesting that their accuracy benefited from having additional time to process the information.

Additionally, the non-parametric alternative to the repeated measures ANOVA indicated that both students with and without SLDs performed worse on visual than on textual questions. Moreover, the findings revealed that faster response time were generally associated with lower accuracy. Unfortunately, no interaction effect between student Group (TD vs. SLDs)*Time (Slow, Medium, Fast)*Type of question (Textual vs. Visual) was observed, which would have supported the results of the correlational analyses. This absence of interaction may be attributable to the imbalance in group size between students with SLDs (N = 45) and with TD (N=291).

The fourth study, instead, explored the relationship between WM components (verbal and visuospatial) and students' performance in a chemistry task comparing students with and without SLDs. The investigation involved 87 students with TD and 21 with SLDs. First, we compared their cognitive profile, and we observed that the two groups have similar estimated IQ and visuospatial WM score. However, the students with SLDs performed worse than students with TD in the verbal WM task. This result was coherent with literature (Callens et al., 2012; Pizzigallo et al., 2023; Toffalini et al., 2017) reporting that people with SLDs frequently have lower score in verbal WM tasks. Furthermore, the two groups' performance in the chemistry task had been compared, and the results showed no significant difference in terms of accuracy, nevertheless students with SLDs were slower compared to peer with TD. Additionally, the correlational analysis highlighted that total score at the chemistry task was moderately and positively related to visuospatial WM score among students with and without SLDs, and the correlation was even stronger among students with SDLs. Finally, we ran two linear regression analyses (one for the TD group and one for the SLDs group), implementing the same model in both groups. The model was significant only among students with SLDs showing that: slow students (those who employ more time to fulfil the final task) perform better if they reach a high score in the visuospatial WM task, while slow students with SLDs who reached lower scores at the visuospatial WM task performed significantly worse. In other words, it can be hypothesized that students with SLDs with low competence in the visuospatial WM might struggle more in dealing with chemistry. These results have important educational implication, because the commonly used compensatory tool during a chemical exam, which is extra-time, may not be sufficient if they lack compensatory tools to support their WM skills.

The two investigations that have been carried out in chapter four (fifth and sixth study) had the objective to investigate whether the introduction of dynamic animation could promote students understanding in a chemistry learning task. We used the same procedure of the previous studies, but we assessed students with and without SLDs in two different conditions: static vs. dynamic. The fifth study investigates students with typical development, comparing whether the performance in static vs. dynamic condition is different. The statistical analyses pointed out no significant difference. A recent meta-analysis (Castro-Alonso, Wong, et al., 2019) concluded that dynamic representation can positively affect science learning (including chemistry), but the effect-sizes are highly heterogenous, suggesting that multiple factors could moderate the efficacy of using dynamic visual tools (see also, Berney & Bétrancourt, 2016; Höffler & Leutner, 2007). Therefore, to grasp a more complete understanding of the beneficial aspects of introducing dynamic representations, it is necessary to extend and include in our framework the cognitive aspects. For this reason, we assessed students' WM (both verbal and visuospatial components), and general cognitive ability (estimated intelligence quotient – IQ). This further investigation revealed valuable findings: the two groups (static vs. dynamic

condition) were significantly different in terms of cognitive abilities. The dynamic group performed significantly worse in all the three cognitive tasks. Nevertheless, the two groups did not perform differently in the chemistry learning task. Furthermore, the correlational analysis showed that the estimated IQ was positively related to chemistry task, and the relationship was stronger in the dynamic group. This result was in accordance with current literature (Castro-Alonso, Ayres, et al., 2019; Peeters et al., 2023) which acknowledges that dynamic visualizations are associated with a higher cognitive load than static ones. Moreover, the analysis pointed out that chemistry learning task performance was moderately related to visuospatial WM components in the static group, whereas it was weakly related to the verbal components in the dynamic group. The results in the static group confirmed what is well established in literature (Rhodes et al., 2016; St Clair-Thompson & Gathercole, 2006): that visuospatial WM components are related to students' accuracy in a chemistry learning task. On the other hand, the correlational results in the dynamic group highlight that students' accuracy was weakly and non-significantly related to visuospatial WM, and it was weakly related to verbal WM. These results suggested that students in the dynamic group had to deal with complex visual information as well as with verbal ones, and this placed a greater load on their verbal WM components and their general cognitive ability compared to the static group (Castro-Alonso, Ayres, et al., 2019). Consequently, we implemented two separated non-parametric ANOVAs comparing how students with low, medium and high visuospatial WM score performed in the textual and in the visual questions. Differences between the three groups (low, medium, and high) emerged only in the static condition, whereas their performance was comparable in the dynamic one. These suggested that dynamic animations could be a valuable resource for students with low visuospatial WM ability. Finally, to better understand whether the cognitive aspects (verbal WM, visuospatial WM and estimated IQ score) were differently related to chemistry task performance in the two conditions (static vs. dynamic) we implemented a step-wise regression analysis considering the whole sample. It emerges that both in static and dynamic conditions students with higher verbal WM scores performed better; likewise, students with higher estimated IQ scores performed better in both conditions. We hypothesize that the verbal WM and estimated IQ score, were significant predictors because, in the current assessment, students were deprived of the professor's visual cues and could only hear his explanation. As a result, the task placed greater demands on verbal WM than in the previous investigation, requiring students to rely more extensively on their verbal processing capacities. Furthermore, we observed a significant interaction effect, visuospatial WM*condition, suggesting that the introduction of dynamic animations can support students with low visuospatial WM. On the other hand, the interaction Estimated IQ*condition was not significant. Overall, this final analysis confirmed that dealing with dynamic animations loads up on general cognitive ability (Castro-Alonso, Ayres, et al., 2019; Castro-Alonso et al., 2015; Peeters et al., 2023), as well as they may offer a valuable support for students with low visuospatial WM skills. This has also some precious educational implication, such for example that the implementation of dynamic visualizations within the lecture, can scaffold students in understanding complex topic more effectively. Furthermore, they can support students that struggle more in generating mental representation, since they have more problems when are asked to deal with visuospatial information.

Finally, the sixth study was an explorative study that attempts to extend the investigation about static vs. dynamic visualisation tools among students with SLDs. We assessed these students with the same chemistry task implemented in the fifth study, and we compared their performance with a matched group of students with TD. Firstly, we investigated how the two groups of students with SLDs (static vs. dynamic) performed in the chemistry task. The analyses showed no significant differences. However, the average scores in the dynamic group was slightly lower as well as the students in the dynamic group took more time to fulfil the task compared to the static group. This may be attributed to the higher cognitive load associated with processing dynamic animation, that has already been demonstrated (Castro-Alonso et al., 2015; Peeters et al., 2023). Coping with dynamic visualisations (such as video, animations or augmented reality) could be complex from a cognitive point of view, due to their fleeting nature (Castro-Alonso et al., 2015). Castro-Alonso et al. (2015) review the existing literature about dynamic visualisation tools, and they observed that one of the negative aspects of these tools is their transiency. According to the author the physical or virtual manipulation as well as the gestures could represent a valid option to overcome the issues related to dynamic visualization tools. However, all the investigations that they reported did not target students with SLDs. Therefore, we narrowed down the investigation on a sub-sample, $N = 20$ (10 static and 10 dynamic conditions) of students with SLDs that took part in the cognitive assessment too. The two groups had a comparable cognitive profile (similar scores in the verbal and visuospatial WM tasks, and similar estimated IQ scores), and their performance in the chemistry task was comparable. Finally, we carried out a final analysis comparing these students' performance in the chemistry task with a matched group of students with typical development (TD). The students were matched for verbal and visuospatial WM tasks, gender, and estimated IQ scores. The non-parametric ANOVAs revealed that in the static condition the students with SLDs perform comparable to their peers with TD; on the contrary, in the dynamic condition, instead, the former performed significantly worse in the total score and in the visual questions.

In summary, taken together these findings demonstrated that the two WM components are differently related to the students' accuracy in answering the 10 multiple-choice questions of the chemistry task. In particular, evidence from multiple studies indicates that accuracy in our chemistry learning task was related to visuospatial WM components, and this pattern had been observed both in students with TD and with SLDs, especially when they are exposed to static version of the video-class. Conversely, this evidence was not replicated when we introduced the dynamic condition. This inconsistency leads us to an interesting consideration, that this evidence may be partially related to the nature visuospatial WM task (De Beni et al., 2008; Richardson & Vecchi, 2002) employed in the research. The task requires the active manipulation of static visuospatial information, hence, when students are in the dynamic condition and have to process animated visualizations of sub-microscopic representations, the chosen task did not capture this dynamic aspect of visual processing. However, this first evidence raises an important implication: it suggests that the implementation of visualisation tools may enhance students' understanding of chemistry topic that strongly solicit visuospatial WM abilities. Such tools could be particularly beneficial for students with low visuospatial WM

abilities, that often struggle to create mental representations. Furthermore, the present investigation extends the current knowledge on students with SLDs, indicating that they experience more difficulty with verbal questions and they may benefit from the use of picture-based questions, which reduce the overload on reading processes. However, when students with SLDs were compared to peers with TD with similar estimated IQ and visuospatial WM scores, their accuracy in a chemistry task was comparable. On the other hand, students with SLDs were significantly slower in processing and required more time to complete the final test and performed worse in the verbal WM task. Hence, these findings confirmed that adults with SLDs have more difficulties in processing verbal information than peers with TD (Pizzigallo et al., 2023), and that they need more time compared to students with TD to deal with complex learning task (like the one we designed for the present investigation). Therefore, providing these students with additional time or allowing them to break down the material they need to study for exams into smaller parts could represent reasonable adjustments to promote academic success. This is particularly relevant in higher education, where scientific subjects (like chemistry) reach a high level of abstraction and ask students to deal continuously with concepts that rely both on phonological and visuospatial processes.

The second aim of the present research was to explore whether the introduction of visualization tools could support students' understanding of a chemistry topic. To this end, we assessed students using two different version of the recorded video-class about liquid crystal: in the static version, molecular structures were presented as simple picture, while in the dynamic one, these images were replaced with short animated video showing the same molecular structure rotating. In fact, it has been reported that among younger students with SLDs the implementation of video-based mathematics instruction can improve students problem-solving performance (Kellems et al., 2020). Similar results were observed using video modelling to teach geometry problems (Satsangi et al., 2020) or mathematics (Morris et al., 2022). Therefore, we attempt to explore what happens among university students with and without SLDs. Overall, our findings led to the conclusion that the simple introduction of short videos of molecular structures may serve as a valid tool for students with TD who have lower visuospatial WM ability. However, such short videos did not enhance performance of students with SLDs in the chemistry learning task. Our observation of students with TD corroborate with literature (Ardac & Akaygun, 2005; Linn et al., 2006; Stieff, 2011), which reports that the introduction of dynamic animation can promote students' understanding of concepts related to sub-microscopic level. By contrast, the results of the comparison between students with and without SLDs in the dynamic condition, showed that students with SLDs performed significantly worse compared to students with TD when exposed to dynamic condition. This output suggests that the passive exposition to dynamic visualisation tool could be not effective among students with SLDs. One possible explanation is that multiple factors moderate the efficacy of using dynamic visual tools (see for example, Berney & Bétrancourt, 2016; Castro-Alonso, Wong, et al., 2019; Höffler & Leutner, 2007) as well as such tools can overload cognitive resources (Castro-Alonso, Ayres, et al., 2019). In particular, weaknesses in verbal WM (Daniel et al., 2022; Pizzigallo et al., 2023; Toffalini et al., 2017) combined with the complexity of processing transient video presented simultaneously with verbal explanations, may generate cognitive overload among students with SLDs.

Overall, our findings contribute to a better understanding of the relationship between chemistry learning and WM components (verbal and visuospatial), as well as about the effects of using static vs. dynamic visual tools to explain sub-microscopical chemistry concepts in students with and without SLDs. Nonetheless, several limitations should be acknowledged. First, we were able to involve a small sample of students who completed both the chemistry task and the cognitive assessment. Participation was voluntary and without compensation, which made it challenging to recruit a larger cohort, particularly among students with SLDs. Future investigation should include larger samples to strengthen the robustness and generalizability of the present conclusions. Second, we did not collect measures of self-perceived cognitive load. Future research should include this aspect, especially those considering the efficacy of the introduction of dynamic video, in order to determine whether students with and without SLDs report higher levels of self-perceived cognitive load when processing complex visual information. Third, the present investigation was restricted to comparing static vs. dynamic visualisation tools. However, in literature (see Chapter 1, section 1.5) there are examples of other different visualisation tools that can be implemented and that require a more active role of learners. We made this choice because we wanted to test the efficacy of a visualization tool that could be easily implemented by lectured during everyday class. Nevertheless, we are well aware that different and more structured visualization tool are available, hence, future research should investigate for example whether the implementation of interactive tools, (such as the manipulation of 3D computer-based models on a smartphone or computer screen, or the use of immersive virtual reality) may produce stronger learning benefits. These approaches could provide learners with a more active role, though their effects on cognitive load remain inconclusive (Elford et al., 2022; Peeters et al., 2023). Fourth, when we designed the final multiple-choice test (see chemistry task) we did not investigate whether the implementation of the same question using verbal or visual coding could make the difference. In particular, we are referring to Q6, that was designed as one of the most difficult visual questions. However, it could be interesting in future research to investigate whether the use of verbal coding could lead to different findings. The concept of chirality (core aspect of Q6) is verbally explained by the lecturer using visual representation as a support; hence it would be interesting to explore what would change presenting the question as textual one. Fifth, we measured the time employed to execute the chemistry task, as the seconds to answer to all the ten questions and we did not measure the item-level response time. The lack of this data limits our ability to explore the relationship between question' accuracy and time to answer the question. Future investigation should include a more detailed measurement of this aspect, in order to study whether conceptual questions elicit longer response times. Additionally, this data could help us in better understand the correlational results between time and accuracy among students with and without SLDs that emerged in study 3 (chapter 3). Finally, the present research did not assess students' individual re-elaboration of the lesson content. Specifically, we did not examine how students used the 10 minutes allocated for individual study, nor did we evaluate the quality of any notes they might have taken, given that note-taking was not mandatory. However, there is substantial evidence in the literature supporting the positive effects of concept maps as helpful tools for promoting chemistry learning (e.g., BouJaoude & Attieh, 2003; Markow & Lonning, 1998; Regis et al., 1996; R. M. Wong et al., 2021). Although

these tools have not been specifically investigated among students with SLDs, they may represent a valuable resource for enhancing conceptual understanding in this population. Future research should address this limitation by investigating how students with and without SLDs re-elaborate and consolidate the information presented during video lessons, exploring whether compensatory tools such as concept maps can further support their learning. Despite these limitations, the present investigation offers valuable insights with important implications for education. They suggest that the simple introduction of dynamic visual tools is not sufficient to enhance chemistry understanding among students with SLDs. Furthermore, educators should recognize that some learners may require additional time to process information when are presented with complex visual or verbal material. These students' understanding could be facilitated by reducing the amount of information presented simultaneously within the animations and by providing them with verbal explanation sequentially, rather than concurrently with the video, as additional scaffolding to support their processing of the visual material.

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Appendix 1: Original pool of questions for the Chemistry Task (CT)

Lyquid Cristals Final Test – Original Questions

Textual Questions

Question 1.

Quando è stato coniato il temine cristallo liquido? [When was the term 'liquid crystal' first used?]

- Nel 1991 [In 1991]
- Nel 1888 [In 1888]
- ***Tra la fine del XIX e l'inizio del XX secolo [Between the end of the XIX century and the beginning of the XX century]***
- Nel 1792 [In 1792]

Comment:

First, the correct alternative is the only one in which numbers are not involved. The alternatives 1991 and 1888 are both actual dates, but the correct answer requires a three-step process. Students have to inhibit any incorrect dates that may be stored in their memory. The correct answer must be inferred: in the video-recorded explanation it says, *"Few years after 1888 the term 'liquid crystal' was introduced".* In other words, students have to infer that corresponds to the end of the 19th-20th century. Finally, it asks the students to decode the Roman numerals.

Final choice

It has been included but reformulated as it follows:

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]

Question 2.

La classificazione primaria dei cristalli liquidi si fonda su [The primary classification of liquid crystals is based on:]

- *Il modo in cui il cristallo liquido interagisce con la luce* [The way in which the liquid crystal interacts with light]
- ***Il fenomeno all'origine di questo stato fisico*** **[The phenomenon behind this physical state]**
- *La temperatura di transizione di fase* [The temperature of phase transition]
- *Tutte le voci precedenti* [All previous responses]

Comment:

The correct answer is too generic, to be included should be reformulated.

Final choice

The question has been included but reformulated as it follows:

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]

Question 3.

La classificazione secondaria dei cristalli liquidi si fonda su: [The secondary classification of liquid crystals is based on:]

- ***La struttura dei mesogeni*** **[The structure of mesogens]**
- *La densità della mesofase* [The density of the mesophase]
- *Il modo in cui i mesogeni si organizzano microscopicamente a fromare il cristallo liquido* [The way mesogens organize themselves microscopically to form the liquid crystal]

- *Nessuna delle precedent* [None of the above]

Comment:

Given the structure of the question and the structure of the lesson, the question may be too complex. It should be include more information in the slides to help students navigate between primary, secondary, and tertiary classification of liquid crystal during the independent study phase.

Final choice

Excluded

Question 4.

Nella fase nematica [In the nematic phase:]

- *Sono presenti mesogeni discotici* [Discoid mesogens are present]
- ***I mesogeni sono disposti (in media) secondo una direzione preferenziale*** **[Mesogens are arranged (on average) according to a preferred direction]**
- *I mesogeni presentano un ordine posizionale* [The mesogens have a positional order]
- *I mesogeni si distribuiscono in piani sovrapposti che possono scorrere gli uni sugli altri* [The mesogens are distributed in overlapping planes that can slide over each other]

Comment:

In relation to the content, it is satisfactory. However, it would be preferable for it to be reworded in a clearer manner so as to avoid an overabundance of reading material that might have a negative effect on the correct response.

Final choice

Included, but it was reformulated as it follows:

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]

Question 5.

Nella fase smettica C: [In the smettic C phase:]

- *Non è riconoscibile alcun ordine direzionale* [No directional order is recognizable]
- *Il direttore e la normale del piano coincidono* [The director and the normal of the plane coincide]
- ***Il direttore foorma un angolo con la normale del piano*** **[The director forms an angle with the normal of the plane]**
- *I mesogeni sono sempre chirali* [Mesogens are always chiral]

Comment:

The question is satisfactory in its overall structure; however, it should be noted that there are three alternatives that are highly similar and one that is significantly divergent. This could potentially enhance students' ability to respond correctly.

Final choice

Included, but it was reformulated as it follows:

Nella fase smettica C: [In the smettic C phase:]

- *Non esiste un direttore preferenziale* [There is no preferential director]
- *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]**
- *Il direttore e la normale del piano coincidono* [The director and the normal to the plane coincide]

Question 6.

Nella fase discotica, i mesogeni possono disporsi a formare: [In the discoid phase, mesogens can arrange themselves to form:]

- *Sfere* [Spheres]
- *Filamenti* [Filament]
- *Piramidi* [Pyramids]
- ***Colonne*** **[Columns]**

Comment:

It was observed that the question was of a relatively elementary nature when evaluated in comparison with the level of complexity exhibited by the other questions, and it was posited that this may have resulted in a ceiling effect.

Final choice

Excluded

Question 7.

La fase nematica con struttura chirale è anche detta: [The nematic phase with chiral structure is also called:]

- *Discotica* [Dicotic]
- *Calamitica* [Calamitic]
- *Anisotropa* [Anisotropic]
- ***Colesterica*** **[Cholesteric]**

Comment:

It was observed that the question does not imply understanding but only memorization.

Final choice

Excluded

Question 8.

Il campo elettrico può orientare i mesogeni di una fase colesterica in modo che: [The electric field can orient the mesogens of a cholesteric phase so that:]

- ***Il piano della luce polarizzata non subisca una rotazione*** **[The plane of polarized light does not undergo rotation]**
- *La struttura chirale sia preservata* [The chiral structure is preserved]
- *La polarizzazione della luce venga annullata* [The polarization of light is canceled]
- *Essi si dispongano in modo casuale e disordinato* [They are arranged in a random and disordered manner]

Comment:

The question is satisfactory in its general conception; however, it would benefit from a process of rewording. This question could serve as an effective tool for evaluating students' deep-level of understanding of the topic, as well as their capacity to establish connections

between the sub-microscopic and macroscopic levels. In this regard, it would be beneficial to refine the inquiry by focusing on the pixel that turns on or off depending on the presence or absence of the chiral structure when the electric field is off or on, respectively.

Final choice

Included, but it was reformulated as it follows:

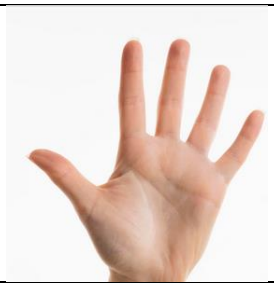
Quando si accende il campo elettrico in un pixel di uno schermo LCD [When the electric field is switched on in a pixel of an LCD screen:]

- ***La fase chirale non è presente e il pixel risulta spento*** **[The chiral phase is not present, and the pixel is switched off]**
- *La fase chirale è presente e il pixel risulta acceso* [The chiral phase is present, and the pixel is switched on]
- *La fase chirale è presente e il pixel risulta spento* [The chiral phase is present, and the pixel is switched off]
- *La fase chirale non è presente e il pixel risulta acceso* [The chiral phase is not present, and the pixel is switched on]

Visual Questions

Question 1.

Quale delle seguenti immagini non corrisponde ad un sistema chirale? [Which of the following images does not correspond to a chiral system?]

		X	
			

Comment:

The ability to answer this question requires having internalized the concept of chirality and inhibiting the confusing information about "hand" presented in the video-class in order to understand what chiral systems are. However, the choice of a sphere could cause confusion; replace it with the image of a chair.

Final choice

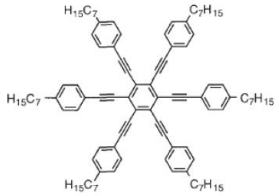
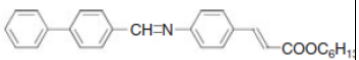
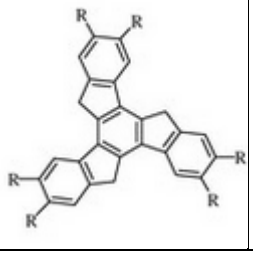
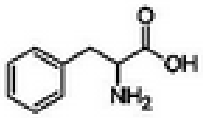
It has been included but reformulated as it follows:

Quale delle seguenti immagini non corrisponde ad un sistema chirale? [Which of the following images does not correspond to a chiral system?]

		X	

Question 2.

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		
			

Comment:

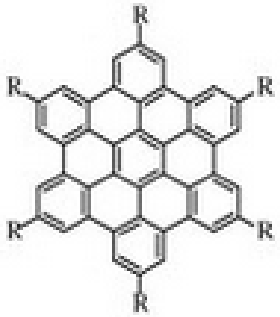
This question is well formulated, and the ability to answer correctly depends on having associated the verbal information, the word "calamitic structure," with the image of the corresponding structure reported in the slides.

Final choice

The question has been included exactly as it was originally formulated.

Question 3.

Osserva la figura sottostante. A quale termine ritieni che possa essere associata? [Look at the figure below. Which term do you think it can be associated with?]

	*Prolato* [Prolate] *Calamitico* [Calamitic] ***Discotico* [Discotic]** *Smettico* [Smectic]

Comment:

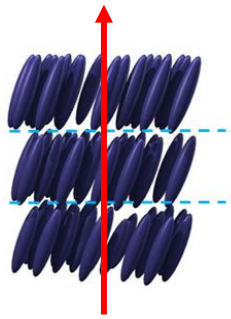
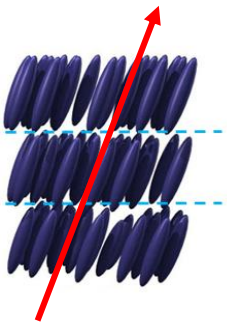
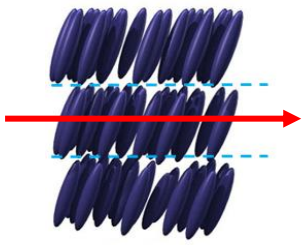
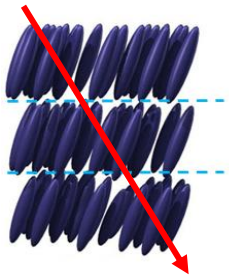
In order to ensure consistency with the other questions, it is recommended that the answer options comprise images. The structure of the question is too simple; this may result in a ceiling effect.

Final choice

Excluded

Question 4.

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		
			

Comment:

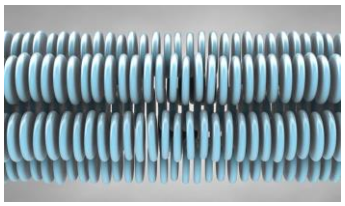
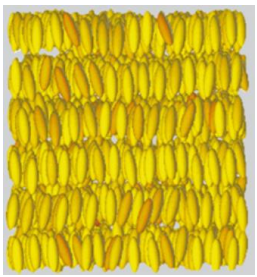
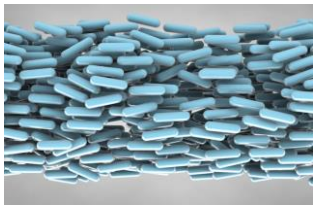
This question has been formulated in a satisfactory manner. The ability to answer correctly requires a superficial level of understanding and the ability to inhibit the confounding concept of "normal of a plane".

Final choice

The question has been included exactly as it was originally formulated.

Question 5.

Quale delle figure sottostanti corrisponde ad una fase nematica? [Which of the following pictures correspond to a nematic phase?]

			X
			

Comment:

The question has been formulated in an adequate manner. Correct answers to this question require a deep-level of understanding and the ability to inhibit the confounding structures reporting molecular structures similar to the target and to those present on the slides.

Final choice

The question has been included exactly as it was originally formulated.

Question 6.

Quale termine associeresti alla sottostante rappresentazione? [Which term would you associate with the representation below?]

	***Discotico nematico* [Nematic discotic]** *Solido cristallino* [Crystalline solid] *Smettico* [Smectic] *Colonnare* [Columnar]

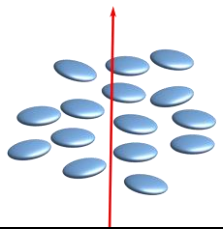
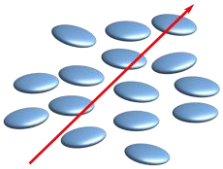
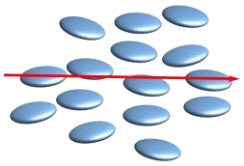
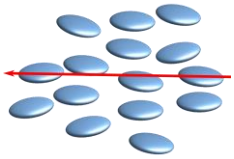
Comment:

In order to ensure consistency with the other questions, it is recommended that the answer options comprise images. The content of this question is suitable, but the question should be transformed in a conceptual question. In order to this, the attention should be on the concept of director applied to the nematic discotic phase.

Final choice

Included, but it was reformulated as it follows:

Quale è il corretto direttore per una fase nematica discotica? [Which picture properly identifies the director in the discotic nematic phase?]

X			
			

Question 7.

Quale delle seguenti rappresentazioni non corrisponde ad un cristallo liquido? [Which of the following representations does not correspond to a liquid crystal?]

			X

Comment:

It was observed that the question was of a relatively elementary nature when evaluated in comparison with the level of complexity exhibited by the other questions, and it was posited that this may have resulted in a ceiling effect.

Final choice

Excluded

Appendix 2: Students' performance at the chemistry task (CT) in static vs. dynamic condition: the case of natural science students

The two conditions (static vs. dynamic) include a heterogeneous sample of students enrolled to different degree courses. In order to better understand the differences in students' performance in the two conditions, we choose to narrow down the attention focusing on a sub-sample of students enrolled to the same degree course (Natural Sciences). Therefore, we ran the analyses again, but the results confirmed the previous conclusion as no significant difference was observed (see Table 1).

Table 1. Mean (M) and standard deviation (SD) for the accuracy (number of correct answers) in the CT as well as the time for the static and dynamic conditions: the case of Natural Science students

	Static (N=33; 48.48% female)		Dynamic (N= 47; 57.45% female)			
	M	*SD*	*M*	*SD*	*U*	*p*
Total score	5.52	2.05	5.62	2.21	756	0.847
Textual score	3.15	1.06	3.11	1.18	771	0.964
Visual score	2.36	1.25	2.51	1.38	742	0.763
Factual score	60.61%	25.02%	64.89%	24.07%	714	0.534
Conceptual score	51.52%	24.07%	50.35%	26.35%	761	0.885
Time (in seconds)	404	131	476	85	534*	0.018

We observed no significant difference between the two groups in terms of accuracy, but it can be noticed that the students in the dynamic conditions took more time to complete the final text.