DE GRUYTER Chemistry Teacher International 2025; 7(4): 633–646

Special Issue Paper

Shelley Rap*, Ron Blonder, Moran Bodas and Debora Marchak

Can chemistry knowledge influence student behavior? A neuropedagogy-based intervention as good practice to address cognitive and affective learning factors

https://doi.org/10.1515/cti-2025-0014
Received January 31, 2025; accepted September 2, 2025; published online September 17, 2025

Abstract: Behavioral science research highlights that knowledge alone does not ensure behavior change, since decision-making is influenced by cognitive, emotional, and social dimensions. To address the knowledge-behavior gap and foster knowledge-based decision-making and agency in high-school chemistry students during the COVID-19 pandemic, we developed a nano-chemistry learning unit contextualized in public health. It was designed using neuropedagogical instructional principles to support conceptual and personal meaning-making processes by considering the cognitive, affective, and social aspects of learning. After its implementation in high-school chemistry classrooms (10th-12th grades), the unit was evaluated through structured interviews conducted with six students 8–12 months after its completion. Students found the learning experience engaging, interactive, and much different from traditional lessons. They highlighted chemistry's relevance to real-world challenges, particularly COVID-19. Retention was evident; students accurately recalled nano-chemistry concepts, visual representations, and mechanistic explanations related to mask functionality months after the intervention. Students' perceptions shifted from viewing mask-wearing as mere compliance to recognizing its role in preventing infection. Some students proactively shared their knowledge. Findings from this evaluation suggest that neuropedagogy-based strategies that integrate active learning and contextualization might be a suitable approach to foster agency and participation. Further research should explore the role in supporting meaningful educational outcomes.

Keywords: agency; neuropedagogy; context-based learning; integrative learning; public health; active learning; ECRICE 2024

1 Introduction

The OECD[1] Learning Compass 2030 framework defines a "new normal" in education, emphasizing the affective, social, and cognitive aspects of learning alongside procedural, epistemic, and content knowledge. Central to this transition is supporting student agency, which is defined as the capacity to set goals, reflect, and act responsibly to effect change, and support making a decision at cognitive, social, and affective levels.[2,3] Agency develops through real-world, social, and material interactions that enable developing the above-mentioned foundational skills.

***Corresponding author: Shelley Rap**, Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel, E-mail: shelley.rap@weizmann.ac.il. https://orcid.org/0000-0001-6896-6184
Ron Blonder and Debora Marchak, Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel. https://orcid.org/0000-0003-4796-4678 (R. Blonder). https://orcid.org/0000-0002-0026-8870 (D. Marchak)
Moran Bodas, Department of Emergency & Disaster Management, School of Public Health, Gray Faculty of Medical and Health Sciences, Tel Aviv University, Tel-Aviv-Yafo, Israel. https://orcid.org/0000-0002-6182-6362

Moreover, agency is context-specific; different forms of agency, such as political, social, artistic, and scientific, require applying agency-related foundational skills within specific contexts to achieve context-specific goals.[3]

The unprecedented disruptions caused by the COVID-19 pandemic provide a stark example of how diminished agency can affect individuals' behavior, particularly in the realm of public health adherence. The COVID-19 pandemic brought extraordinary restrictions on individual freedoms, leading many to experience a profound sense of reduced agency.[4,5] This loss of control over personal and societal circumstances had significant implications regarding compliance with health regulations. Psychological theories suggest that a perceived lack of agency can induce frustration, stress, and helplessness, undermining motivation to adhere to external demands.[6] Moreover, individuals may exhibit psychological reactance, resisting rules they perceive as infringing on their autonomy. Such behaviors are often amplified when restrictions are perceived as overly rigid or inconsistent with individuals' values or needs, particularly in younger audiences.[7]

A lack of agency may also erode trust in authorities, further diminishing compliance. This distrust is exacerbated when individuals feel excluded from decision-making processes, fostering the belief that regulations are imposed without considering their needs or perspectives. Consequently, feelings of exclusion and disempowerment can contribute to lower levels of public cooperation regarding accepting health measures.[8–10] Behaviorally, reduced agency can lead to disengagement from protective practices, since individuals may feel that their actions have little impact, consequently becoming apathetic or fatalistic.[11,12] Some may respond by engaging in risky behaviors to regain a sense of autonomy, even against health guidelines.[13] These dynamics highlight the need for public health strategies that address the psychological and behavioral impacts of reduced agency to improve compliance during crises. Similar patterns are observed in other contexts such as climate change, where knowledge alone has a limited effect on behavior, and psychological, social, and emotional factors play a greater role.[14–18] Behavioral science studies have explored the gap between knowledge and behavior, highlighting the need for innovative approaches to bridge it.[19] Thus, if knowledge alone is not enough to influence behavior, what can be done at the educational level?

Education can serve as a powerful tool to equip students with the knowledge and skills needed to develop agency and effectively address such challenges. This could be valid for scientific subjects such as chemistry, which is known as a central science[20] and constitutes an essential part of the solution for many real-world challenges. Nevertheless, studies suggest that high-school students often find chemistry irrelevant to their daily lives, which may explain their declining interest in pursuing advanced studies in it.[21–25] According to Aikenhead[26], the science content taught in schools rarely applies to real-life situations, leading many students to struggle with finding the material meaningful, even if the context appears somewhat relatable. One possible reason for this perceived irrelevance is the separation between science and society in chemistry education.[27]

Thus, the perceived irrelevance of chemistry might hinder the role of chemical education as an agentic factor and highlights the importance of adopting context-based learning (CBL) approaches when teaching chemistry in combination with approaches that target affective and social aspects of learning to link chemistry to students' personal experiences and offer them opportunities to consider chemistry as personally meaningful. CBL approaches help students develop logical frameworks for understanding chemistry.[24,28] They emphasize applying scientific concepts to real-world situations, enhancing students' comprehension while also preparing them to engage as responsible citizens in their everyday lives.[26,29]

A fundamental aspect of the CBL approach is the "need-to-know" principle, which suggests that student engagement and retention can be enhanced if a genuine need to acquire knowledge or skills is recognized during learning.[23] The "need-to-know" principle implies that the context should justify the learning of content from the student's point of view, thus ensuring that learning is both valuable on a personal level and relevant in external contexts. To encourage student agency in the context of CBL, the learning environment should enable students to undergo learning experiences through which foundational skills can be acquired in parallel to knowledge[30] under the lens of real-world scenarios and while considering varied aspects of learning.

With the aim of advancing knowledge-based decision-making and agency in chemistry students and influencing student behavior regarding pandemic-related regulations, we developed the present unit, which contextualizes nano-chemistry in public health. To address the cognitive, affective, and social aspects of learning integratively, the unit was developed by considering instructional design principles that were found to be effective in supporting conceptual meaning-making as well as personal meaning-making processes by using the neuropedagogical approach, as explained below. Following the development of this well-structured unit about the science behind the imposed public health regulations, we set out to explore its possible impact on high-school chemistry students' behavior regarding the regulations. Next, we describe the development, implementation, and evaluation phases in detail.

2 Unit development

2.1 Theoretical considerations

The unit's goal was to create an integrated learning environment that might influence adolescents' knowledge and behavior regarding pandemic-related regulations such as wearing masks. For this reason, and given the weight that affective and social factors have on adolescent decision-making[31], we considered the cognitive aspects of learning alongside the affective and social aspects. To tag chemical content as relevant during learning, this unit is intended to support both conceptual meaning-making (sense-making) and personal meaning-making mechanisms. Sense-making can be broadly defined as the process through which one understands or grasps; input is decoded into information and logical meaning is constructed. It involves processing input in working memory by integrating it with stored memories through reasoning and conceptualization.[32] Although sense-making is strongly based on cognitive processing mechanisms, it was shown that one can completely understand something at a certain instance and yet forget it shortly after.[33] It is probable that, in these cases, personal value was not assigned and related emotional tagging was weak. Emotional involvement is essential for memory to generate and consolidate (stabilize in time and be stored as long-term memory). Consequently, assigning personal meaning to content is important in educational settings, and it is related to the perceived relevance and value of the content learned. The process through which one assigns personal meaning to input and attributes personal significance to experiences, events, information, and emotions is defined as personal meaning-making.[32] It is a cognitive process directed by emotional tagging, and as such it is strongly related to memory formation[34] as well as to affect and social interactions.[35]

A neuropedagogical approach was employed to address the above-mentioned cognitive, affective, and social aspects of learning through teaching. In neuropedagogy (NP), insights from the neurosciences regarding how the brain learns are incorporated into the educational sphere with the aim of enhancing and optimizing instructional practices and thus learning processes.[36,37] NP advocates for the influence that instruction has on students' brain development through teaching-learning interactions; namely, that crafting these interactions through NP-informed instructional design is expected to support learning. A cornerstone of NP is reconciling cognition and emotion by recognizing the affective and social aspects of learning as integral to learning, investment in learning, and achievement.[38]

Nano-chemistry and public health, supported by NP, were integrated by adapting the Neuropedagogy-based, Multidisciplinary Learning Grid model of integrative learning (NP-MLG)[39] to design the research-based scaffold that would guide the development of the unit's activities. NP-MLG is a conceptual "space" designed to assist the process of developing integrative science learning experiences by applying neuropedagogical principles expected to make learning more efficient and address learning holistically. It is a well-structured yet flexible instructional design framework that allows accommodating various learning modalities. NP-MLG is essentially multidisciplinary in nature and spans a three-dimensional space composed of a specific scientific subject dimension, a neuropedagogical dimension, and a third dimension integrated with science. The choice of the integrated dimension may have different purposes: to serve as a pedagogical tool (contributing content, procedural, and epistemic knowledge from a different field) or as a contextualization framework for science (situating the scientific core discipline in real-world scenarios).

The integration of advanced research fields, such as nano-chemistry, into high school science education presents an ongoing challenge within the science education community.[40,41] Several studies have explored potential points of integration between nanotechnology and the high school science curriculum.[42–44] The program developed and presented in the current study offers an additional approach to update scientific curriculum content by incorporating visualization-based materials that illustrate advanced concepts from nanotechnology research within the context of health-related issues.

2.2 From theory to instructional design

In line with the unit's goal, the learning grid for developing the activities presented here materialized from the intersection between Nano-Chemistry, Public Health, and Neuropedagogy (Figure 1). The specific components of each of the three dimensions of the adapted learning grid were defined by considering the content to be taught as well as the desired learning outcomes of learning through the unit. After evaluating them, we identified three suitable pedagogical strategies through which we could implement the neuropedagogical principles in this unit, namely, active learning, social and emotional learning, and visual literacy strategies. Consequently, these pedagogical strategies were adapted to be implemented by using the neuropedagogical approach by selecting those neuropedagogical principles that we considered to be essential to support sense-making and personal meaning-making in the framework of the developed unit (see Figure 1, Neuropedagogy axis).

Active Learning (AL) refers to a learning experience whereby the learner is actively involved in the process of constructing knowledge and gaining skills. It applies to the instructional approaches whereby participants take an active role in the learning process, in contrast to the more passive role that they have in the lecture-based modes of learning.[45] Active learning has been shown to enhance student engagement, as well as their critical thinking abilities, knowledge retention, and overall learning outcomes.[46] It is widely recognized as a valuable approach in educational settings, ranging from primary and secondary schools to higher education as well as professional development programs[47–49] In the context of the unit presented here, the employed AL strategies include activating information-processing pathways other than the visual-aural ones, e.g., speech and movement while conducting most of the lesson by engaging in collaborative problem solving, exploratory learning, and student-led discussions using puzzles, dilemmas, and riddles.

Social and Emotional Learning (SEL) is a combined process through which individuals acquire new knowledge and skills through interaction and shared experiences. The SEL framework is centered on developing

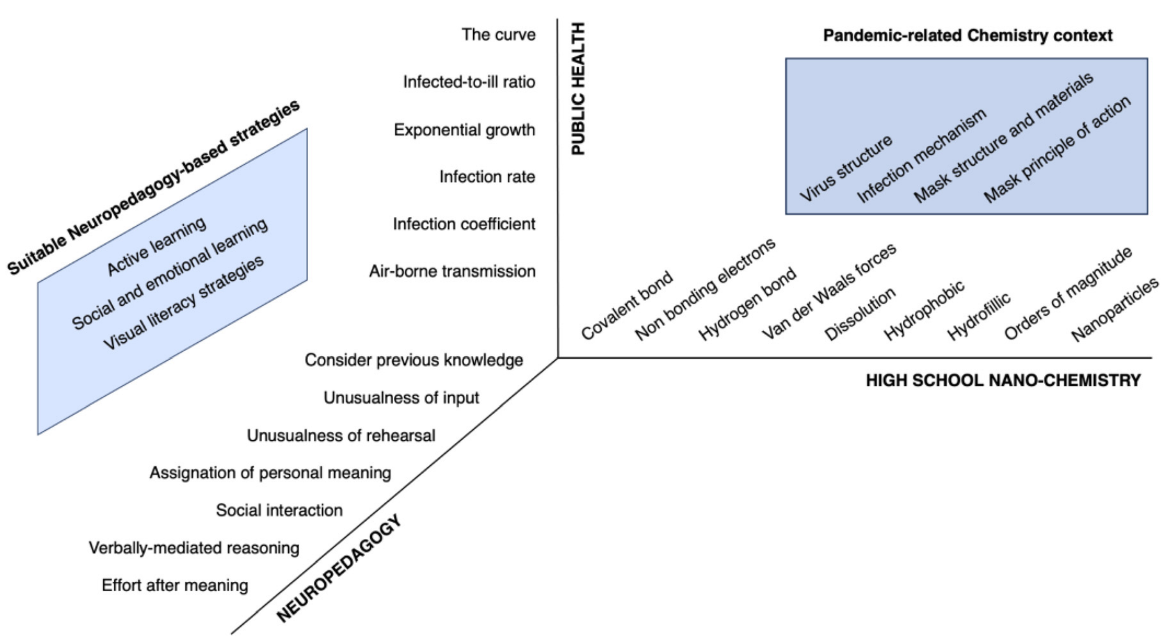

Figure 1: Schematic diagram of the three-dimensional conceptual space of the neuropedagogy-based, public health integrating, high-school nano-chemistry learning grid.

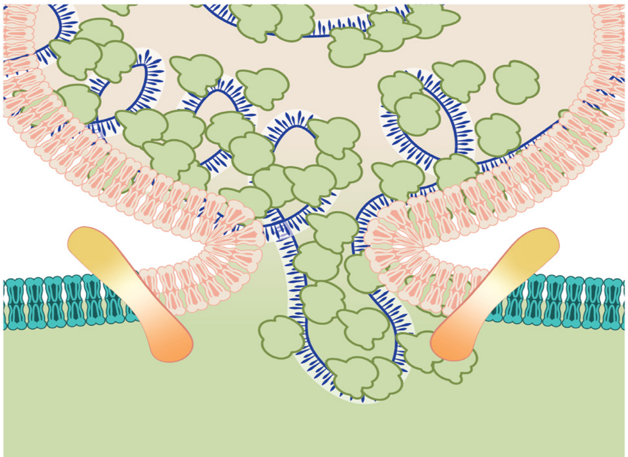

Figure 2: Illustration of the fusion between the virus and the human cell membrane.

emotional and social intelligences. It emphasizes the need for developing students' social and emotional skills not at the expense of cognitive ones, but rather as essential for supporting overall well-being and growth.[50] SEL can take place when learning occurs in a social environment where the circumstances allow for attributing personal meaning, for negotiating opinions and ideas, and for re-shaping attitudes, behavior, values, and beliefs.[51,52] For example, in this unit, SEL as a strategy implies engaging in pair and group work, which naturally involves expressing self-generated output in argumentation, co-construction of shared semantic expressions in collaborative tasks, and knowledge negotiation. In all cases, the need for communication involves the external use of language in reasoning and requires greater mental effort. SEL also becomes apparent in this unit when students are invited to participate in discussions, solve dilemmas, share their own opinions, and discuss them in a group. Emotional tagging connected to emotional arousal loops is expected to occur whenever self-expression is involved[53], increasing the chance of attributing personal meaning to content.

Visual Literacy Strategies (VLS) are pedagogical strategies that aim at facilitating the development of visual literacy skills in students. Visual Thinking Strategies (VTS)[54] is one such strategy and was found effective in imparting visual literacy skills.[55] It introduces art and visual images as tools to enhance creative and critical thinking, as well as communication skills. In the NP-MLG model, the original VTS approach was combined with other visual literacy fostering methods,[39] and adapted to support the challenges that chemistry students face when dealing with scientific visual representations of chemical content. Several studies have shown that verbal reasoning to integrate verbal and non-verbal input in visualization supports learning in chemistry when complex visual representations of content are involved [56–58]. In this unit, students are given longer observation times to interact with the images and are then asked to engage in the verbal mediation of visual images while reasoning. They are guided by the task to analyze the given images and find semantic expressions of their evaluation (self-generated output), then discuss their interpretations, and finally answer carefully crafted questions about the given images. Figure 2 is an example of one such image that students were requested to analyze through a VLS task while learning in the presented unit. The picture depicts the moment when the virus and the human cell membrane fuse and the genetic material of the virus is free to enter the human cell intracellular space. In addition, given the graphical nature of pandemic-related information disseminated in the media, as well as the need to visualize abstract images to internalize chemical content in this unit, visual literacy was emphasized by implementing an adapted version of the VTS approach.

3 The unit's form and content

The unit presented here consists of four consecutive lessons, each focusing on different topics chosen hierarchically, in growing levels of organization: Lesson 1: The virus, Lesson 2: The pandemic and related concepts, Lesson 3: Masks, and Lesson 4: Planning for action (Further details are provided in the Supplementary Material). As mentioned above, the unit was developed to actively engage chemistry students in integrating previous knowledge learned in the chemistry classroom (see Figure 1, High School Nano chemistry axis) with new content from the field of public health (see Figure 1, Public Health axis). Specifically, nano-chemistry concepts and terms were contextualized in public health, and students were requested to explore chemistry topics under pandemic-related contexts such as virus structure, infection mechanism, mask structure and materials, as well as the masks' principle of action, from the molecular to the process levels (see Figure 1, Public Health and Nano Chemistry axes intersection).

A summary of the unit in terms of topics and contextualization appear in Table 1. The neuropedagogical principles employed in this unit are also described in detail in Table 1, including a short elaboration on how they took shape in relation to each lesson in the unit, its topic, and pedagogical goals.

4 Implementing the unit

Through the circulation of advertising posters in relevant social media, chemistry teachers were invited to participate in a short (45 min) online workshop open to all teachers at the national level. Here, they were exposed to the unit materials that were then made available to all. In addition, the research team was fully available to address implementational questions from teachers as required. The unit was implemented in the classrooms; it consisted of four lessons of 90 min each. A detailed description of the sequence of implementation by lesson follows.

Lesson 1 - The Virus as a Molecular Machine: The lesson starts by revising previous knowledge on molecular structures, functional groups, and intermolecular forces. Revision takes place through a multiple-choice worksheet on which students work in pairs and then discuss their answers when the teacher presents them. Then, the teacher teaches the topics of the orders of magnitude, the virus structure, and the infection mechanism through a second presentation with carefully crafted visuals and short videos. The revised content is connected to the new terms and concepts being taught. To close this lesson, students work in pairs and engage in a puzzle-like activity in which they are asked to apply previous and newly gained knowledge to assemble, chronologically, a three-vignette story of the infection mechanism and then write explanatory captions regarding the images, using chemical terms to describe the depicted processes.

Lesson 2 - The Pandemic and Us: This lesson focuses on the pandemic through the lens of Public Health. Students begin by answering a quick, individual quiz to recap what they know, or think they know, about how to behave according to media-disseminated regulations. Then, they engage in group work where each group analyzes one of many news stories about COVID-19. Tasks here require analyzing diagrams, graphs, and texts, each touching on a pandemic-related concept or term such as asymptomatic transmission of the virus, the case-fatality ratio, flattening the curve, and virus variants. Each group is asked to learn about a given term or concept, summarize the information and teach their peers about it through a short presentation. After that, students are asked to complete an individual questionnaire that presents them with regulations-related behavioral dilemmas. After they have completed the questionnaire, the teacher poses the question, "After what we have just learned, how is the pandemic connected to me, to the community?" and then leads a class discussion on how the pandemic affects each of us personally, and how our own behavior can make a difference in slowing down its transmission. The lesson ends by watching a short humoristic video (YNET, 2020) about thoughtless behavior regarding regulations, showing that the virus can be spread through everyday interactions, which are most common and, in non-pandemic times, sociably accepted.

Lesson 3 - The Chemistry of Masks: The third lesson starts by asking students to visit an emulated exhibition set up on the classroom's walls, showing historical pictures of different masks and people wearing masks from previous times in history. Throughout the exhibition, students are requested to understand that pandemics and wearing masks are not new events in human history. Then, students move to a display simulating a kiosk of a "Mask Market", where students are exposed to all types of masks that are sold in shops and pharmacies. Students are asked to select a mask from the display and explain why they chose it. After sharing their choices, the teacher

Table 1: Summary of the unit.

Lesson and topic	Contextualization of chemistry in public health	Neuropedagogical principles and related pedagogical strategies
1. The virus	– Revision of relevant previous knowledge (intermolecular forces) – The virus as a molecular machine: the role of functional groups and intermolecular interactions in the virus structure – Orders of magnitude – Optical and electron microscopy	– Considering previous knowledge to 1) decrease the working memory load, and 2) integrate new input with long term memory – Verbally mediated reasoning: Guided decoding of the pictorial representations of chemical and biological metaphorical entities (rehearsing visual literacy skills: observation, evaluation, and interpretation of visual representations of molecules, viruses, membranes, and more) – Social interactions (working in pairs to organize vignettes depicting the chemistry of the virus infection mechanism)
2. The pandemic and related concepts	– Infection coefficient, infection rate, the curve, exponential growth, the relationship between infected people, and the percentage of seriously ill patients	– Unusualness of input and the assignation of personal meaning: dealing with public health-related dilemmas from a personal standpoint – Verbally mediated reasoning: Guided decoding of graphic representations of numerical data (rehearsing visual literacy skills: observation, evaluation, and interpretation of plots, charts, and diagrams) – Social interactions (working in groups to complete riddle-like tasks) – Self-generated semantic expression and oral production (presenting riddle-like tasks' outcomes to peers) – Assignation of personal meaning and self-expression: discussing the dilemmas again and sharing personal insights
3. Masks	– Historical evolution of masks – The materials from which masks are made: polymeric molecular materials in relation to hydrophobic/hydrophilic – The structure of the knitting in the mask + orders of magnitude + microscopy – Additions to the mask: metallic nanoparticles as anti-viral agents + orders of magnitude + microscopy	– Unusualness of input: participating in an in-class exhibition of images showing masks and people wearing various types of masks throughout history – Effort after meaning: interpreting bizarre images related to the historical evolution of masks, based on previous knowledge–Verbally mediated reasoning: Guided decoding of pictorial representations of chemical metaphorical entities (rehearsing visual literacy skills: observation, evaluation, and interpretation of visual representations of hydrogen bonds, macro-molecules, and nanoparticles) – Verbally mediated reasoning: Guided decoding of microscopy-related images (rehearsal of visual literacy skills: observation, evaluation, and interpretation of pictures of fabrics used for masks taken with SEM) – Unusualness of input, personal decision-making, and self-expression: participating in an in-class market showing various types of modern masks, choosing a mask and sharing chemistry-based reasons for choosing it
4. Planning for action	Integrating all the topics that appeared in the unit so far and the connections between topics in relation to the m-RNA vaccine and its mechanism of action.	– Unusualness of rehearsal: implementing unit-related content in hypothetical problem solving (textual and visual scientific literacies task – in lesson 4) – Unusualness of rehearsal: implementing unit-related content in real problem solving, creative elaboration, oral production (poster preparation and dissemination of knowledge through presentation in the community – after lesson 4)

Figure 3: Scanning electron microscope images of different types of masks.

explains the chemistry of masks, covering topics such as hydrophobicity/hydrophilicity, polymer molecules and polymeric materials, the structure of masks' layers, and the role of nanoparticles that serve as anti-bacterial and anti-viral surfaces. During this section of the lesson, chemistry topics revised and learned during lesson 1 and public health topics learned in lesson 2 are integrated through the teacher's explanations and thereafter during a summative activity. The summative activity begins with a short video from the news where the presenter compares different masks in terms of filtering efficiency and price. Students are requested to evaluate the statements made in the video through inquiry methods and by applying chemistry content that the teacher taught. To do so, students must analyze the images of masks taken with a Scanning Electron Microscope (Figure 3) and use the information inferred from these images combined with concepts from polymeric materials at the molecular level. To close the lesson, students revisit their earlier mask choice based on the chemistry of the various types of masks and indicate whether their opinion has changed now that they know more about the science behind it.

Lesson 4 - Taking Knowledge into Action: The fourth lesson is an integrating lesson. Students are asked to engage in a scientific literacy task requiring them to employ central ideas and skills learned through the unit: discussing the science behind governmental regulations, understanding m-RNA vaccines through nano-chemistry concepts taught during the unit, recalling the basics of how droplets spread the virus and why masks help, based on the chemistry of masks. Teachers can consider this task as a short test and grade it. After students complete the task, the teacher explains to them about socio-scientific activism, what activism means, and how one can take social action by disseminating research-based, scientific knowledge in the community. In small groups, and guided by driving questions delivered through a worksheet, students are asked to choose a preferred community-reaching activity, such as making informative posters, sharing knowledge on social media, or organizing mask donations. After planning the activity, students are required to submit their plan. The teacher can also encourage them to execute the planned activity, thus conveying to them that she trusts them as agents of change and encourages them to actively utilize their understanding of integrated nano-chemistry and public health.

The expected chemistry learning outcomes from participating in this unit can be understood in terms of the different lessons' themes. During the lessons' progression, the students are offered the opportunity to apply curricular chemistry content learnt in class in varied contexts: to explain the virus infection mechanism, to understand the science behind public health terms that they hear in the media, to understand the chemical properties of the materials used in masks and how these works, and to know the chemistry related to the design of mRNA vaccines. Moreover, regarding behavioural outcomes, we expected that by the end of the unit, we would see a change in students' behavior regarding mask-related regulations.

5 Evaluation

5.1 Description of the population

Before implementing the educational unit described here, we sought to map and identify chemistry students' general knowledge and attitudes regarding pandemic-related issues and the coronavirus. As reported in the literature, students' knowledge and attitudes could be significant factors influencing their behavior. To assess these factors, a brief survey was conducted among 78 chemistry high-school students. The survey examined their existing knowledge of chemistry related to the COVID-19 pandemic, their general public health knowledge, and attitudes towards the recommended behaviors during the pandemic. Additionally, some questions were designed to elucidate their actual behavior concerning mask-wearing.

The survey was conducted in May-June 2021, during a period when mask-wearing in public spaces was mandatory and vaccines against COVID-19 were not yet available in Israel. The findings revealed that students' knowledge of chemistry related to the pandemic (e.g., the size of the virus or the effectiveness of fabric masks) was relatively limited. However, their understanding of public health measures associated with desirable behavior (e.g., "isolating infected individuals is an effective way to reduce virus transmission" or "mask-wearing reduces the spread of COVID-19") was notably strong.

Regarding attitudes, students expressed a general dislike for wearing masks but also reported concerns about the possibility of a family member contracting COVID-19 and believed that they had an impact on reducing the virus's spread. However, it became evident that despite their knowledge of appropriate pandemic-related behavior and their concerns about spreading the virus to dear ones, their actual behavior did not consistently align with the recommended practices. Specifically, students often refrained from wearing masks in social settings, particularly in informal or private environments such as at home or in cars, even though they acknowledged its importance in formal settings like schools or shopping centers. The survey findings point to the discrepancies between knowing the right behavior and behaving appropriately among the student population, together with their prioritization of social life. These findings align with existing literature [17,59] and emphasize the importance of developing educational units that address the emotional and social dimensions related to knowledge-behavior gaps. Examples of similar gaps were shown to exist pertaining to "drinking and driving" as well as environmental issues [17,60].

5.2 Description of the Evaluation Methodology

The educational unit was implemented with 120 high-school chemistry students in grades 10–12 (age 16–18 years old) at the national level. We decided to evaluate the impact of the unit and how it was perceived by students. For this purpose, we recruited a convenience sample of six students who voluntarily agreed to participate in structured half-hour interviews [61] conducted 8–12 months after they had completed the unit. At the time of the interviews, mask-wearing in public spaces was recommended; however, it was no longer mandatory in Israel, and vaccines against COVID-19 were widely available.

The interview included 11 open-ended questions designed to examine students' learning experiences after participating in the unit, what they remembered from the unit in terms of content knowledge, as well as the unit's possible impact on their behavior. The questions asked during the interview pertained to (1) students' feelings and perceptions during the lessons, (2) their willingness to actively share the knowledge they acquired with others, (3) the relevance of this knowledge to their daily lives, and (4) how this knowledge could affect their decision-making in hypothetical scenarios. Through these questions, students were asked to freely elaborate on what they remembered from the lessons, particularly concerning chemical content, and to explain public health terms in their own words. Some questions focused on assessing the integration of verbal and non-verbal representations of chemical content, since, for this purpose, verbally mediated reasoning was employed broadly throughout the implementation of the unit. In these questions, students were shown illustrations signifying complex chemical meaning taken from the materials used in the unit and were asked to describe the illustrations. This approach aimed to assess their ability to translate visual inputs into semantic expressions through verbally mediated reasoning. The questions as they were asked during the interviews follow:

(1) When the term "COVID-19" is mentioned, what thoughts come to mind?
(2) Do you recall studying about COVID-19 and masks during the pandemic in your chemistry lessons? What specific concepts do you remember from those lessons?
(3) Please reflect on your experiences during those lessons. How did you find the learning environment and the content taught?
(4) Did you share the content that was taught during those lessons with anyone else? If so, could you elaborate on what you shared?
(5) How did what was taught during those lessons assist or influence you in your daily life?
(6) [The interviewer displays an illustration of the viral infection mechanism (Figure 2)] Please describe what can be seen in this illustration.
(7) When the term "flatten the curve" is used, to what does it refer?
(8) [The interviewer displays an electron microscope magnified image of a mask (Figure 3)] Please describe what can be seen in this image.
(9) How does a mask prevent viral transmission?
(10) Hypothetically, if a new variant named "Oxy-Micron" starts to spread tomorrow, which is highly contagious and its severity is not yet clear, would you choose to wear a mask? Please elaborate on your decision.
(11) Is there anything else you would like to contribute based on your experience during the lessons?

The interviews were recorded, transcribed, and analyzed by qualitative research methods. The data were coded and categorized sequentially [62], beginning with an initial solo-coding phase, followed by a collaborative coding phase to refine the emerging categories. The analysis sought to reveal students' subjective experiences during the lessons and their subsequent effects, emphasizing the use of visual aids to facilitate long-term retention of content.

6 Results and discussion

The results of the narrative qualitative analysis indicate that the neuropedagogy-based learning unit impacted students on three primary levels: affective, cognitive, and behavioral. A summary of the key findings is presented below:

As can be seen in the representative quotes shown in Table 2, students' answers revealed retention of chemical content and conceptual understanding. When exposed to the illustration of the viral infection mechanism, most students proceeded to explain the viral infection mechanism in terms of the chemical entities and the intermolecular forces between them involved in this mechanism (question 6). When exposed to an electron microscope magnified image of masks' fibres in question 8, most students could correctly identify masks' structural features and then, explain how different masks work (or do not) to prevent exposure to the virus based on intermolecular forces, hydrophilicity and hydrophobicity.

In order to produce their narrative explanations, students must not only to recall visual information on the visual elements in display, but also to retrieve related chemistry concepts and relationships through which to interpret and explain the meaning of the images. Students' answers shed light on the possible transduction of abstract chemistry concepts and their metaphorical association with the visual images displayed. Thus, through these narratives, we gain evidence that the integration of non-verbal (visual) and verbal (conceptual) information might have taken place, depending on the scientific accuracy of the answers.

Although this evaluation focused on the subjective experiences of six students, overall, the insights gained are valuable. The findings support the suitability of designing instruction to incorporate neuropedagogical principles in educational settings, particularly when addressing complex, real-world topics such as public health during the COVID-19 pandemic. The neuropedagogical, integrative approach employed in the learning unit seems to have

Table 2: Summary of the key findings.

Category	Key findings	Representative quotes
Affective impact	Students found the learning experience enjoyable and interactive, describing it as much different from traditional lessons. It also aroused interest in the chemistry profession. Emotional engagement emerged as closely tied to cognitive effects, since students expressed interest in terms of relevance and personal meaning attributed to chemical content (Barrett, 2017; Sousa, 2011).	"I would be happy if other subjects were taught like this… It was relevant to everyday life and fun to learn. Honestly, considering all the times we were taught this subject, in chemistry class it was the most enjoyable… It helped me see that everything has chemistry. Even regarding COVID-19, which is biological, there is chemistry. Now, I always see chemistry everywhere… "
Cognitive impact	Students' recall of chemistry content related to pandemic topics was evident. They correctly employed nano-chemistry concepts to explain mask functionality, viral interactions, and visual elements related to the mask structure. This suggests successful integration of nano-chemistry concepts possibly through verbal and non-verbal input integration (Paivio, 2014), semantic elaboration (Craik & Tulving, 1975), and effort after meaning (Zaromb & Roediger, 2009) guided by employing visual literacy strategies (Housen, 2002) throughout the unit.	"The teacher showed it to us in class… (describing Figure 2); the hydrogen bonds stick to parts of the cell or the body and with the help of the bonds, they get closer to each other until the corona comes together… (describing Figure 3); there are different types of masks for use under the microscope. Surgical masks are the best because they are arranged in alternating layers. The cloth mask is not as good as the surgical mask because it does not have the hydrophobic part."
Behavioral impact	Students shifted from compliance-driven mask-wearing to proactive engagement to prevent infection, based on their scientific understanding. They shared knowledge about mask functionality with their family and peers, exemplifying agency development driven by personal meaning and decision-making (Blakemore, 2008; Levine & Edelstein, 2009).	"I always look for logic behind doing something and don't do things just because someone said so. It's always nice to know there's a reason… When it's connected to chemistry, it makes you take things more seriously… It changed something in my behavior… The "reason" is what changed my opinion. Before, I did it because of fines and laws; now it's because I understand how to act to stop the infection and end the pandemic… I found it interesting and wanted to share it with my family and friends."

had a positive impact on students' affective, cognitive, and behavioral engagement. This unit seems to have elicited a learning experience that facilitated a deeper understanding and long-term retention of complex concepts. The deliberate incorporation of contextual chemistry applications and visual literacy strategies exemplifies how neuropedagogy-informed integrative practices have the potential to transform traditional learning environments into more dynamic and impactful educational experiences [63].

Our findings regarding the possible impact of the unit on students' knowledge, emotional engagement, and behavior are valuable within the framework of the OECD Learning Compass 2030 [1], which emphasize the development of student agency as a core educational outcome of explicitly addressing agency-supporting skills in formal educational settings. The findings suggest that the neuropedagogy-based, integrative learning unit possibly fostered agency by encouraging students to move beyond merely incorporating knowledge toward active engagement in the learning process, while contextualizing the core scientific subject in a real-world scenario.

Despite the restrictions on personal freedoms imposed during the COVID-19 pandemic, such as mandatory mask-wearing, which may have initially diminished students' sense of agency [4,5], participation in the unit appeared to counteract these effects. Some students reported a shift from passive compliance to informed, purposeful decision-making, enabling students to better understand and internalize the scientific rationale behind mask usage. This transition aligns with the notion that fostering agency significantly enhances students' cognitive and social development, since they take ownership of their learning and apply it meaningfully beyond the classroom setting [64–67].

In today's rapidly evolving world, cultivating student agency is essential [68]. Empowering students to make informed decisions and take meaningful actions prepares them to effectively navigate and address complex societal issues. Research indicates that fostering student agency not only contributes to individual growth, butit also promotes positive societal change, since students become better equipped to address and influence issues that affect them and their communities [64,68,69]. Thus, educational approaches that prioritize the development of agency are crucial for preparing students to meet contemporary challenges with confidence and competence. Building on the importance of agency, the integration of NP in chemistry CBL seems to positively influence not only knowledge but also the development of thinking skills and understanding, processes that support agency. Further research and development should address this evidence-based hypothesis.

7 Limitations and further research

As mentioned in the Description of the Evaluation Methodology, during the large-scale implementation of the unit, a change in regulations regarding mask-wearing occurred. This shift introduced a key challenge to the evaluation of the intervention's implementation, potentially affecting both the context and the behavior of the participants. It also required substantial adjustments to the evaluation methods to align with the new circumstances. While the study originally planned as a quasi-experimental study, these unanticipated changes limited the ability to isolate the effects of the intervention and fully assess behavior change by the implementation of the quantitative tools. Furthermore, the relatively small sample size, though consistent with qualitative methodologies, further constrains the generalizability of the findings. Given these factors, the study should be viewed as exploratory, offering preliminary evidence of the intervention's potential impact. Future research with a larger sample applying the quantitative tools will be essential to explore the hypotheses in depth and better establish mechanisms of influence and possible causal relationships.

Acknowledgments: This study was supported by Miel de Botton.
Research ethics: The research received the following ethical approvals: The Weizmann Review Board of Education (IRB-EDU) Approval on 11.5.21. The Ministry of Education Approval (ID 11745) on 9.5.21.
Informed consent: Not applicable.
Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.
Use of Large Language Models, AI and Machine Learning Tools: We made minimal use of ChatGPT to refine language of a few isolated paragraphs.
Conflict of interest: The author states no conflict of interest.
Research funding: This study was supported by Miel de Botton, The Weizmann Institute of Science P133329.
Data availability: Not applicable.

References

1. OECD. An OECD learning framework 2030. In *The Future of Education and Labor*; Bast, G., Carayannis, E. G., Campbell, D. F. J., Eds.; Springer International Publishing: Cham, 2019; pp 23–35.
2. Burkitt, I. Relational Agency: Relational Sociology, Agency and Interaction. *Eur. J. Soc. Theor* **2015**, *19* (3), 322–339.
3. Shogren, K. A.; Little, T. D.; Wehmeyer, M. L. Human agentic theories and the development of self-determination. In *Development of Self-Determination Through the Life-Course*; Wehmeyer, M. L., Shogren, K. A., Little, T. D., Lopez, S. J., Eds.; Springer Netherlands: Dordrecht, 2017; pp 17–26.
4. Nurain, N.; Caldeira, C.; Connelly, K. Older adults' experiences of autonomy during COVID-19 pandemic.In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, Yokohama, Japan, 2021.
5. Martela, F.; Hankonen, N.; Ryan, R. M.; Vansteenkiste, M. Motivating Voluntary Compliance to Behavioural Restrictions: Self-Determination Theory–Based Checklist of Principles for Covid-19 and Other Emergency Communications. *Eur. Rev. Soc. Psychol.* **2021**, *32* (2), 305–347.
6. Ryan, R. M.; Deci, E. L. Self-Determination Theory and the Facilitation of Intrinsic Motivation, Social Development, and Well-Being. *Am. Psychol.* **2000**, *55* (1), 68–78.
7. Miller, C. H. Persuasion and psychological reactance: the effects of Explicit, high-controlling language. In *The Exercise of Power in Communication: Devices, Reception and Reaction*; Schulze, R., Pishwa, H., Eds.; Palgrave Macmillan UK: Basingstoke, 2015; pp 269–286.

8. Bodas, M.; Peleg, K. Pandemic Fatigue: the Effects of the COVID-19 Crisis on Public Trust and Compliance With Regulations in Israel. *Health Aff.* **2021**, *40* (8), 1225–1233.
9. Bodas, M.; Wine, L.; Peleg, K. Public Conformism with Health Regulation is Crumbling as COVID-19 Becomes A Chronic Threat: Repeated Cross-Sectional Studies. *Isr. J. Health Pol. Res.* **2023**, *12* (1), 7.
10. Lind, E. A.; Arndt, C. Regulations, fairness and trust. In *Trust and Public Policy: How Better Governance Can Help Rebuild Public Trust, OECD Public Governance Reviews*; OECD Publishing: Paris, 2017; pp 67–85.
11. Fairchild, R. Fatalism and Health Behaviors: Exploring the Context for Clinician-Patient Interactions. *Ann. Nurs. Pract.* **2015**, *2* (4), 1–4.
12. Chon, M.-G.; Kim, S. Fostering Compliance with Covid-19 Guidelines: Insights for Risk Communication Strategies During a Pandemic. *Soc. Sci. J.* **2022**, 1–15. https://doi.org/10.1080/03623319.2022.2049555.
13. Rawn, C. D.; Vohs, K. D. People Use Self-Control to Risk Personal Harm: An Intra-Interpersonal Dilemma. *Pers. Soc. Psychol. Rev.* **2010**, *15* (3), 267–289.
14. Vanderlinden, J.-P.; Baztan, J.; Chouinard, O.; Cordier, M.; Da Cunha, C.; Huctin, J.-M.; Kane, A.; Kennedy, G.; Nikulkina, I.; Shadrin, V.; Surette, C.; Thiaw, D.; Thomson, K. T. Meaning in The Face of Changing Climate Risks: Connecting Agency, Sensemaking and Narratives of Change Through Transdisciplinary Research. *Clim. Risk Manag.* **2020**, *29*, 100224.
15. Colombo, S. L.; Chiarella, S. G.; Lefrançois, C.; Fradin, J.; Raffone, A.; Simione, L. Why Knowing About Climate Change is Not Enough to Change: A Perspective Paper on the Factors Explaining the Environmental Knowledge-Action Gap. *Sustainability* **2023**, *15* (20), 14859.
16. van Valkengoed, A. M.; Steg, L. Meta-Analyses of Factors Motivating Climate Change Adaptation Behaviour. *Nat. Clim. Change* **2019**, *9* (2), 158–163.
17. Busch, K. C.; Ardoin, N.; Gruehn, D.; Stevenson, K. Exploring a Theoretical Model of Climate Change Action for Youth. *Int. J. Sci. Educ.* **2019**, *41* (17), 2389–2409.
18. White, K.; Habib, R.; Hardisty, D. J. How to SHIFT Consumer Behaviors to be more Sustainable: A Literature Review and Guiding Framework. *J. Market.* **2019**, *83* (3), 22–49.
19. Paton, D. Disaster Risk Reduction: Psychological Perspectives on Preparedness. *Aust. J. Psychol.* **2019**, *71* (4), 327–341.
20. Mahaffy, P. G.; Ho, F. M.; Haack, J. A.; Brush, E. J. Can Chemistry be a Central Science Without Systems Thinking? *J. Chem. Educ.* **2019**, *96* (12), 2679–2681.
21. Bennett, J.; Gräsel, C.; Parchmann, I.; Waddington, D. J. Context-Based and Conventional Approaches to Teaching Chemistry: Comparing Teachers' Views. *Int. J. Sci. Educ.* **2005**, *27*, 1521–1547.
22. Broman, K.; Ekborg, M.; Johnels, D. Chemistry in crisis? Perspectives on teaching and learning chemistry in Swedish upper secondary schools. *NorDiNa: Nordic Stud. Sci. Educ.* **2011**, *7* (1), 43–60.
23. Bulte, A. M. W.; Westbroek, H. B.; de Jong, O.; Pilot, A. A. Research Approach to Designing Chemistry Education Using Authentic Practices as Contexts. *Int. J. Sci. Educ.* **2006**, *28* (9), 1063–1086.
24. Gilbert, J. K. On the Nature of "Context" in Chemical Education. *Int. J. Sci. Educ.* **2006**, *28* (9), 957–976.
25. Hofstein, A.; Kesner, M. Industrial Chemistry and School Chemistry: Making Chemistry Studies More Relevant. *Int. J. Sci. Educ.* **2006**, *28* (9), 1017–1039.
26. Aikenhead, G. *Science education for everyday Life: Evidence-Based Practice*, Vol. 5; Teachers College Columbia University, 2006.
27. Van Aalsvoort, J. Logical Positivism as a Tool to Analyse the Problem of Chemistry's Lack of Relevance in Secondary School Chemical Education. *Int. J. Sci. Educ.* **2004**, *26* (9), 1151–1168.
28. Sevian, H.; Dori, Y. J.; Parchmann, I. How does STEM Context-Based Learning Work: What we Know and What we Still do not Know. *Int. J. Sci. Educ.* **2018**, *40* (10), 1095–1107.
29. Bennett, J. Bringing science to life. In *Teachers Creating Context-Based Learning Environments in Science*; Taconis, R.; Brok, P. D.; Pilot, A., Eds.; SensePublishers, 2016; pp. 21–39.
30. Rap, S.; Geller, S.; Katchevich, D.; Gbarin, H.; Blonder, R. Chemistry, Climate and The Skills in Between": Mapping Cognitive Skills in an Innovative Program Designed to Empower Future Citizens to Address Global Challenges. *Chem. Teach. Int.* **2023**, *5* (2), 143–154.
31. Blakemore, S.-J. The Social Brain in Adolescence. *Nat. Rev. Neurosci.* **2008**, *9* (4), 267–277.
32. Sousa, D. A. *How the Brain Learns*; Corwin Press: Thousand Oaks, 2011.
33. Levine, L. J.; Edelstein, R. S. Emotion and Memory Narrowing: A Review and Goal-Relevance Approach. *Cogn. Emot.* **2009**, *23* (5), 833–875.
34. Richter-Levin, G.; Akirav, I. Emotional Tagging of Memory Formation – in the Search for Neural Mechanisms. *Brain Res. Rev.* **2003**, *43* (3), 247–256.
35. Barrett, L. F. *How Emotions are Made: The Secret Life of the Brain*; Macmillan: New York, 2017.
36. Busso, D. S.; Pollack, C. No Brain Left Behind: Consequences of Neuroscience Discourse for Education. *Learn. Media Technol.* **2015**, *40* (2), 168–186.
37. Hardiman, M. Informing Pedagogy Through the Brain-Targeted Teaching Model. *J. Microbiol. Biol. Educ.* **2012**, *13* (1), 11–16.
38. Shvarts-Serebro, I.; Ben-Yehudah, G.; Elgavi-Hershler, O.; Grobgeld, E.; Katzof, A.; Luzzatto, E.; Shalom, M.; Zohar-Harel, T. Agents of Change: Integration of Neuropedagogy in Pre-Service Teacher Education. *Front. Educ.* **2024**, *9*. https://doi.org/10.3389/feduc.2024.1369394.
39. Marchak, D.; Shvarts-Serebro, I. The Multidisciplinary Learning Grid: A Conceptual Space to Develop Neuropedagogy-Based, Arts-Integrated Chemistry Activities. In *Interdisciplinary Insights on Gridded Modalities in Conversation with the Arts*; Bigon, L., Shaked, N., Eds.; De Gruyter: Berlin, 2021; pp 204–224.

40. Jones, M. G.; Blonder, R.; Gardner, G. E.; Albe, V.; Falvo, M.; Chevrier, J. Nanotechnology and Nanoscale Science: Educational Challenges. *Int. J. Sci. Educ.* **2013**, *35* (9), 1490–1512.
41. Jones, M. G.; Blonder, R.; Kähkönen, A. L. Challenges in nanoscience education. In *21st Century Nanoscience–A Handbook: Public Policy, Education, and Global Trends (Volume Ten)*; CRC Press, 2020; pp. 6-1-6–7.
42. Blonder, R.; Sakhnini, S. Finding the Connections Between a High-School Chemistry Curriculum and Nano-Scale Science and Technology. *Chem. Educ. Res. Pract.* **2017**, *18* (4), 903–922.
43. Sakhnini, S.; Blonder, R. Insertion Points of the Essential Nanoscale Science and Technology (Nst) Concepts in the Israeli Middle School Science and Technology Curriculum. *Nanotechnol. Rev.* **2018**, *7* (5), 373–391.
44. Yonai, E.; Blonder, R. Scientists Suggest Insertion of Nanoscience and Technology Into Middle School Physics. *Phys. Rev. Phys. Educ. Res.* **2020**, *16* (1), 010110.
45. Dubinsky, J. M.; Hamid, A. A. The Neuroscience of Active Learning and Direct Instruction. *Neurosci. Biobehav. Rev.* **2024**, *163*, 105737.
46. Markant, D. B.; Ruggeri, A.; Gureckis, T. M.; Xu, F. Enhanced Memory as a Common Effect of Active Learning. *Mind Brain Educ.* **2016**, *10* (3), 142–152.
47. Dori, Y. J.; Belcher, J. Learning Electromagnetism with Visualizations and Active Learning. In *Visualization in Science Education*; Gilbert, J. K., Ed.; Springer Netherlands: Dordrecht, 2005; pp 187–216.
48. Crimmins, M. T.; Midkiff, B. High Structure Active Learning Pedagogy for the Teaching of Organic Chemistry: Assessing the Impact on Academic Outcomes. *J. Chem. Educ.* **2017**, *94* (4), 429–438.
49. Marchak, D.; Shvarts-Serebro, I.; Blonder, R. Teaching Chemistry by a Creative Approach: Adapting a Teachers' Course for Active Remote Learning. *J. Chem. Educ.* **2021**, *98* (9), 2809–2819.
50. Martinez, M. E.; Gomez, V. The Importance of Social-Emotional Learning in Schools. *Acta Pedagogia Asiana* **2024**, *3* (2), 101–112.
51. CASEL Advancing Social and Emotional Learning. https://casel.org/.
52. Vadeboncoeur, J. A.; Collie, R. J. Locating Social and Emotional Learning in Schooled Environments: A Vygotskian Perspective on Learning as Unified. *Mind Cult. Activ.* **2013**, *20* (3), 201–225.
53. Li, L.; Gow, A. D. I.; Zhou, J. The Role of Positive Emotions in Education: A Neuroscience Perspective. *Mind Brain Educ.* **2020**, *14* (3), 220–234.
54. Housen, A. Æsthetic Thought, Critical Thinking and Transfer. *Arts Learn. Res.* **2002**, *18*, 99–131.
55. Hailey, D.; Miller, A.; Yenawine, P. Understanding visual literacy: the visual thinking strategies approach. In *Essentials of Teaching and Integrating Visual and Media Literacy: Visualizing Learning*; Baylen, D. M., D'Alba, A., Eds.; Springer International Publishing: Cham, 2015; pp 49–73.
56. Meyer, D.; Pietzner, V. Reading Textual and Non-Textual Explanations in Chemistry Texts and Textbooks – a Review. *Chem. Educ. Res. Pract.* **2022**, *23* (4), 768–785. https://doi.org/10.1039/D2RP00162D.
57. Langbeheim, E.; Ben-Eliyahu, E.; Adadan, E.; Akaygun, S.; Ramnarain, U. D. Intersecting Visual and Verbal Representations and levels of Reasoning in the Structure of Matter Learning Progression. *Chem. Educ. Res. Pract.* **2022**, *23* (4), 969–979. https://doi.org/10.1039/D2RP00119E.
58. Talanquer, V. The Complexity of Reasoning About and with Chemical Representations. *JACS Au* **2022**, *2* (12), 2658–2669.
59. Albert, D.; Steinberg, L. Peer influences on adolescent risk behavior. In *Inhibitory Control and Drug Abuse Prevention: From Research to Translation*; Bardo, M. T.; Fishbein, D. H.; Milich, R., Eds.; Springer: New York, 2011; pp. 211–226.
60. Allen, J. P.; Brown, B. B. Adolescents, Peers, and Motor Vehicles: the Perfect Storm? *Am. J. Prev. Med.* **2008**, *35* (3, Supplement), S289–S293.
61. Shkedi, A. *The Meaning behind the Words: Methodologies of Qualitative Research: Theory and Practice*; Ramot: Tel Aviv, **2011**.
62. Saldana, J. *The Coding Manual for Qualitative Researchers*; SAGE Publications Ltd: Los Angeles, 2021.
63. Marchak, D.; Shvarts-Serebro, I.; Blonder, R. Crafting Molecular Geometries: Implications of Neuro-Pedagogy for Teaching Chemical Content. *J. Chem. Educ.* **2021**, *98* (4), 1321–1327.
64. Rap, S.; Blonder, R.; Sindiani-Bsoul, A.; Rosenfeld, S. Curriculum Development for Student Agency on Sustainability Issues: An Exploratory Study. *Front. Educ.* **2022**, *7*. https://doi.org/10.3389/feduc.2022.871102.
65. Kangas, M.; Kopisto, K.; Löfman, K.; Salo, L.; Krokfors, L. I'll take care of the Flowers!' Researching Agency Through Initiatives Across Different Learning Environments. *J. Adventure Educ. Outdoor Learn.* **2017**, *17* (1), 82–91.
66. Mallya, A.; Mensah, F. M.; Contento, I. R.; Koch, P. A.; Barton, A. C. Extending Science Beyond the Classroom Door: Learning From Students' Experiences with the Choice, Control and Change (C3) Curriculum. *J. Res. Sci. Teach.* **2012**, *49* (2), 244–269.
67. Rap, S.; Sindiani-Bsoul, A.; Mamlok-Naaman, R.; Blonder, R. Student Agency in sustainability. In *Chemistry Education for a Sustainable Future*; Kirchhoff, M.; Kümmerer, K.; Mahaffy, P.; Middlecamp, C. Eds.; Royal Society of Chemistry, Accepted.
68. Vaughn, M. What is Student Agency and why is it Needed now More than Ever? *Theory Into Pract.* **2020**, *59* (2), 109–118.
69. Cook-Sather, A. Student Voice Across Contexts: Fostering Student Agency in Today's Schools. *Theory Into Pract.* **2020**, *59* (2), 182–191.

Supplementary Material: This article contains supplementary material (https://doi.org/10.1515/cti-2025-0014).