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ORIGINAL PAPER

Chemophobia and practical chemistry: the laboratory as a place of origin or, on the contrary, suppression of the fear of chemistry?

Radek Chalupa[1,2] · **Karel Nesměrák**[3]

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Abstract
From the perspective of the general public, there are a number of ways to describe the doing of science, e.g. experiments, scientific inquiry and laboratory work. In the case of chemistry, however, these activities are united by a single site of performance, the chemical laboratory. Indeed, as early as 1761, Macquer states: "whoever would become a chemist, must indispensably have a laboratory." However, another necessary prerequisite for the successful practice of chemistry is a proper theoretical and practical education. While the theory remains with chemists for the time being, experimental teaching is now in jeopardy. However, limiting laboratory instruction due to perceived excessive cost would ultimately damage chemists' identity and weaken their defences against chemophobia. Hands-on teaching normally associated with the verification of chemical theory in practice, accompanied by an intense dialogue between teacher and student, will not be able to act as a corrective to hostile attitudes towards chemistry. Moreover, its absence may reinforce chemophobia. As a result, the chemistry community may be confronted with a far more dangerous, potentiated chemophobia. The latter would be all the more dangerous because it would operate from within, as a lack of awareness of one's own merit, contribution and self-worth.

Graphical abstract

Keywords Communication strategy · Didactics of chemistry · Fears of chemistry · Identity of chemist · Laboratory training · Public image of chemistry

Introduction

We seem to be witnessing a strange paradox. While the ability to communicate, empathise and listen is finally being identified as a prerequisite for success as a chemist, the experimental skills—the essence of chemical identity—are, according to some, to be discarded. On the one hand, the President of the American Chemical Society, Judith C. Giordan, rightly says that public trust is best gained through dialogue [1]. Accordingly, her goal is to

✉ Radek Chalupa
radek.chalupa@rcceurope.cz

1 Department of Chemistry Education, Faculty of Science, Charles University, Prague, Czech Republic

2 RCC Europe, Ltd, Prague, Czech Republic

3 Department of Analytical Chemistry, Faculty of Science, Charles University, Prague, Czech Republic

provide chemists with strategies and skills to engage with non-scientists to "try to see science from their perspective, share other possibilities, and help them trust you." Giordan therefore wants to strengthen the soft skills of chemists to help them achieve their higher purpose in today's world [2]. On the other hand, some chemists are ready to get rid of the opportunity to learn chemistry experimentally and unnecessarily risk the valuable hard skills of chemists [3, 4]. This in turn can have a major negative impact on the quality of chemistry education and on the ability of students to succeed in practice.

These developments took place against the backdrop of the third year of the COVID-19 pandemic. In this "year of despair" [5], "it has felt like walking through molasses." A lot was seemingly back to normal, but everything we were back to doing was harder won. At the same time, chemists have made great progress in developing new drugs (e.g. for Alzheimer's disease, schizophrenia and cancer) that will change the way medicine is practised [6]. Chemistry has continued to play a key role in achieving the United Nations *Sustainable Development Goal 2: Zero Hunger*, e.g. through its recommendations for crop protection in Asia and Latin America and for bridging ethnic food cultures through chemistry [7]. As Gomollón-Bel and García-Martínez [8] argue, what is now called a polycrisis (i.e. the simultaneous accumulation of several long-term crises) has a chemical solution. This is represented by "emerging technologies", that is, the result of the work of chemical laboratories. These achievements have one thing in common. They have been achieved by people trained in classical experimental chemistry. This has taught them resilience, perseverance and endurance through the efforts of experienced chemists–mentors. Above all, it has taught them to do chemistry well.

Chemists may refer to the current era as the transformative age of chemistry [9]. However, the question remains how to ensure a sufficient number of new chemists with the talents and skills needed for chemistry to face new challenges, especially as more and more students are choosing fields other than chemistry, perceiving them as more lucrative, transparent and impactful career paths. This is all the more so, as society is still unaware of the benefits of chemistry and the influence of chemistry's negative image persists, which can "disillusion younger generations who select careers they believe are more favourable to improving society" [10]. According to a 2023 *Wall Street Journal* poll, 56% of Americans now believe that a college degree is no longer worth the time and money spent on it [11]. In what can be seen as a wake-up call, the poll shows the highest scepticism in the 18–34 age group. At the same time, the number of chemistry students in Germany continues to decline, remaining below 10,000 for the third year in a row [12].

The need to reverse this negative trend has led to efforts to make the study of chemistry more attractive. However, the call for a greater number of non-chemistry electives [13], which should be more relevant to the diverse interests of students, should be accompanied by their proper connection to the world of chemistry. Otherwise, it will lead nowhere. Chemists should take a firmer grip on the interpretation of their discipline and tell the story of our science in the most up-to-date and creative way. In doing so, they will regain their sovereignty of interpretation. In this respect, it is essential that the present and the past of chemistry offer countless opportunities that are still largely untapped, e.g. [14–17]. Thus, the growing interest in communicating chemistry [18–20] may hold welcome promise for future improvements in the perception of the field through both traditional and social media. But we cannot wait. The communication efforts of chemists need to be intensified now. In this respect, the call by the German weekly *Die Zeit* [21] is very appropriate. Scientists are called upon to stop hiding in their ivory towers and become more visible, take part in debates, shape the social discourse on science and master the logic of the media. But, as we suggested in our previous communication [15], this must be done in an effective and sensible way, and, of course, in the interests of chemistry and from its perspective.

However, more fundamental changes may be coming. According to Holme [22], it cannot be ruled out that one potential casualty of the difficult financial situation of universities caused by the COVID-19 pandemic and the associated need for cutbacks will be chemistry laboratory courses. The need to economise may affect their provision, but more fundamental restrictions cannot be ruled out. This is far from the first time that the potential redundancy of laboratory teaching has been mentioned [23, 24]. Recently, a discussion on the importance of laboratory courses in chemistry education has been opened with a curious premise. Bretz [3] argues that "chemists can no longer afford to believe that the importance of laboratory teaching is a truth we hold to be self-evident. As scientists, we must support our research claims with evidence. Our claims about student learning require the same standard." Of course, not everyone agrees with this view [25, 26]. But the Pandora's box has been opened and this may indeed lead to the disruption of laboratory teaching. It is therefore appropriate to summarise the arguments in favour of experimental teaching, to recall the importance of the chemistry laboratory for chemistry, and also to emphasise that it is a place that can, in turn, become an unwelcome source of chemophobia.

Experimental teaching: lessons from the COVID-19 era

In chemistry, more than in other sciences, the famous peripatetic axiom "nihil est in intellectu quod non prius fuerit in sensu" (nothing is in the intellect that was not first in the senses) applies [27]. The importance of simultaneous physical and intellectual knowledge through the practical implementation of chemical operations plays a paramount role in chemistry. After all, the manipulation of matter and its transformation are the very essence of chemistry. In this manipulation lie both the roots of chemistry and its further development for the benefit of mankind [28].

The belief in the importance of hands-on activities in chemistry is reflected in the support for experimental teaching that we have recently encountered. While according to Sansom and Walker [25] this is a unique learning opportunity that fully justifies the cost, Sonbuchner et al. [26] question the ability of virtual laboratories to adequately prepare and inspire future STEM leaders. Moreover, as they put it, "the beauty of science is more difficult to convey online."

The American chemist Laurie R. Stepan believes that young people should be attracted to chemistry through involvement in experimental activities [29]. She recently encouraged them to take an active part in the annual *Chemists Celebrate Earth Day* event. Contrary to the current, often anti-experimental mood in society, she used simple experiments with algae to get them interested in our science. She wanted to show that, thanks to chemistry, we can work together to solve problems large and small, and in doing so, we can save the planet. Stepan believes that this will make a difference. Young people who are encouraged to experiment will become adults who trust scientists and scientific methods.

The chemistry community is currently trying to evaluate the experience of working during the COVID-19 pandemic. The ingenuity [30] with which chemistry educators met the challenges of lockdowns and the associated need for distance learning is rightly highly praised. However, one of the most important lessons is the recognition that nothing can replace face-to-face contact between chemistry teachers and their students. Despite their best efforts, online substitutes of all kinds cannot fully replace this. On the contrary, it is time to pay more attention to laboratory courses as an essential part of chemistry education.

As pointed out by Osborne and Collins [31], the changes that took place in the teaching of chemistry in the last two decades of the twentieth century fundamentally altered students' views of chemistry. Many began to see it as abstruse and far removed from everyday concerns. Teaching became more theoretical, focusing on more fundamental aspects such as atomic and molecular bonding. A number of activities were suppressed, including the manipulation of chemicals, chemical combination and analysis. Due to stricter safety regulations, many of the more "spectacular" demonstrations were eliminated.

Although surveys show that pupils and students are interested in "practical work, laboratory work and demonstrations … as fundamental working methods … to increase interest and motivation for further study of chemistry" [32], these calls often go unheeded. On the contrary, for a number of reasons, experimental education has been reduced and replaced by the teaching of abstract theoretical chemistry, which, however, repels many students and, as a result, alienates them from chemistry [33]. As a result, the teaching of chemistry is being taken back to the eighteenth century, when experimental teaching was rare or non-existent. In the universities of the time, chemistry was treated like a neglected child [34]. Chemistry was taught only as an auxiliary science without any prospect of more fundamental development [35], often by junior teachers [36] or not at all (e.g. at the University of Paris [37]). In classes at universities outside Paris, for example, students saw demonstrations of experiments without the opportunity to try them out [38]. Although they were encouraged to practise what they had seen. Indeed, as Lehman recalls: "it was tacitly accepted that only long practice could really educate the artist." But this depended on the students' own initiative, financial resources and time. Clearly, this limited the possibilities for the further development of chemistry.

However, more than 200 years later, the current attempt to eliminate experimental learning is also in direct conflict with the needs of chemistry education. At the same time, it goes against the wishes of students [39] and long-standing calls for an increase in the number of well-qualified chemists. Simultaneously, as Accettone et al. [40] point out, employers are concerned about the lack of "laboratory-ready" individuals. This is partly related to the fact that students spend about 44% of their time in laboratories compared to the 1960s [41]. Furthermore, the decline in time spent in laboratories represents another tangible loss. At risk are the practical skills such as communication, observation, investigation, reporting, manipulation and discipline as identified by Hofstein and Lunetta [42]. Indeed, these skills, acquired and honed during laboratory chemistry education, along with creativity and aptitude for chemistry, are prerequisites for excellence in chemistry as a science and a discipline.

The history of chemistry is, as it has often been in the past, the history of the struggle for experimental teaching. What Meinel [36] writes about the situation in the second half of the nineteenth century is certainly worth mentioning in this context. According to him, the "quarrel" over whether chemistry, as a purely practical and empirical subject, should be banned from universities was not only about intellectual values. As he recalls: "office and power, competence and influence, salaries and career opportunities, in fact the most tangible values of institutionalised knowledge, were involved."

Desire to experiment

Although most chemists probably do not realise it, performing chemical experiments is always associated with the glorious past of our science. Newcomers to chemistry are keen to verify the experiences of those who came before them. The renowned British neuroscientist and author Oliver Sacks (1939–2015) [43] put it succinctly in his biography dedicated to his "chemical boyhood" in these words: "I longed to have a lab of my own," where he "would enter chemistry … in much the same way as its first practitioners did—I would live the history of chemistry in myself" [44].

A child's natural desire to discover, to make up one's own mind about things and not to be afraid to question "eternal truths" leads, through the verification of these truths, to the roots of chemistry. But the conditions must be created for them to do so. This leads to the realisation that the importance of chemical experimentation is repeatedly illustrated by the life stories of famous chemists. After all, the achievements of modern chemistry are based on their remarkable discoveries, which left their contemporaries in awe [45]. At the same time, they have always served as inspiration to young talents in their decision to study chemistry and devote their professional lives to it. Indeed, the importance of daily hard work is illustrated by a picture from Gaston Tissandier's book *Les Héros du travail* (The Heroes of Work) (Fig. 1). Here, the future discoverer of beryllium and chromium, Louis Nicolas Vauquelin (1763–1829) [46, 47], who came from a poor background, is told by his teacher: "Study so you can dress like that!"

Surprising as it may seem, laboratory teaching does not leave students indifferent, e.g. [39, 48, 49]. According to the research carried out, it stimulates a desire to experiment. A positive response could be seen as recognition of a job well done by the teacher. As the American chemist Zafra M. Lerman, famous for her ability to motivate students to study chemistry [50], once said [51]: "If you make chemistry relevant to the student's life, experience, environment, and interests, you can teach them anything you want, even secondary isotope effects."

As Parchmann et al. [52] remind us, one of the key challenges in chemistry education today is the need to raise young people's aspirations for their studies and subsequent careers in this field of science, to develop their interest and commitment as far as possible and to reinforce this through appropriate practical activities.

However, the experimental nature of chemistry, the fact that it is "a science based entirely on experimentation," places demands on those who wish to study it. Good experimental skills are essential and we certainly cannot do without practical training. As the French chemist Pierre-Joseph Macquer (1718–1784) says, "we cannot hope to understand it well," but neither can we "possess a certain degree of it [i.e. chemistry] without making such experiments" [53] (Fig. 2). Macquer also points out the requirements for doing experiments correctly: "a person must perceive, even in the most common operations, a great variety of small facts, which must necessarily be known, but which are not mentioned … in books … because they are too numerous, and would appear too minute." At the same time, he asks himself: "How many qualities are in the several chemical agents, of which no just notion can be given by writing, and which are perfectly well known as soon as they have been once made to strike our senses?" For this reason, Macquer clearly states that "whoever, therefore, would become a chemist, must indispensably have a laboratory."

Despite the constant complaints about the lack of interest in studying chemistry, a closer look reveals that genuine enthusiasm for chemistry is not always properly encouraged:

- According to Shirazi [54], students expect not only enthusiasm from the teacher, but also their greater involvement in the learning process. The student's demands can be summarised as less "chalk and talk". This means less writing on the board, less theoretical explanations and more experimentation. In the context of online teaching, which proved necessary during the COVID-19 pandemic and whose benefits and further use are now being debated [22, 30], the critical attitude of the participants in the survey towards the overuse of new technologies in teaching is of utmost importance. Indeed, as Shirazi [54] points out, a large proportion of students feel that teachers rely too much on ICT-led teaching (use of PowerPoint presentations and videos).
- Research by Sentanin et al. [55] shows that chemistry experiments are the most likely to stimulate students' curiosity. This finding is supported by the students' own words: "The part of the lecture I thought was the coolest was the experiment."
- Maltese and Tai [48] identify experimentation as one of the most important sources of early interest in inquiry-based science, whether it is part of a classroom activity (as a demonstration, laboratory experiment or science project) or as a hobby in your spare time (experiments done at home).
- According to Osborne and Collins [31], the absence of, or significant limitation of, experimental learning in chemistry classes has a negative effect on attitudes towards teachers. According to the research, students

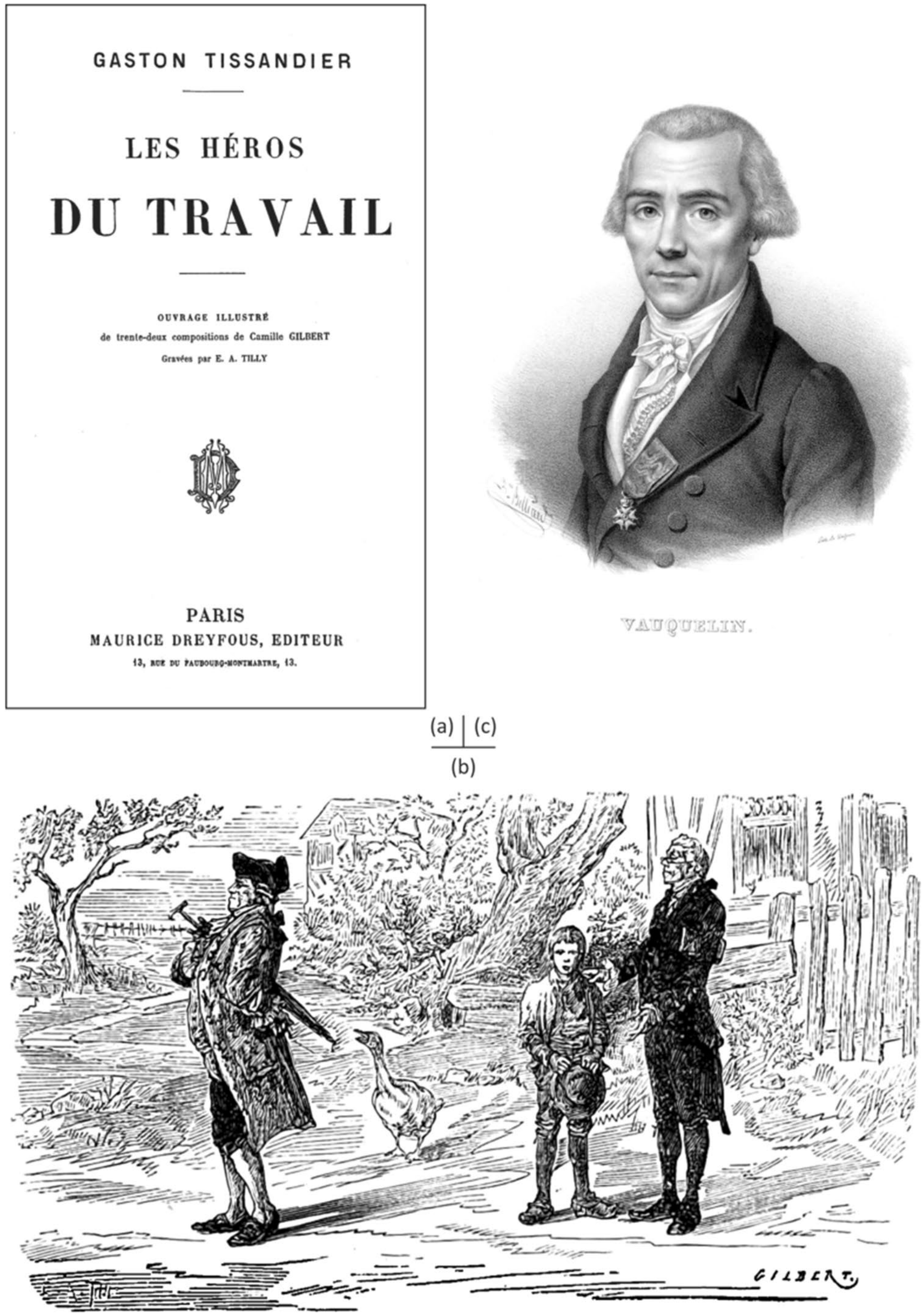
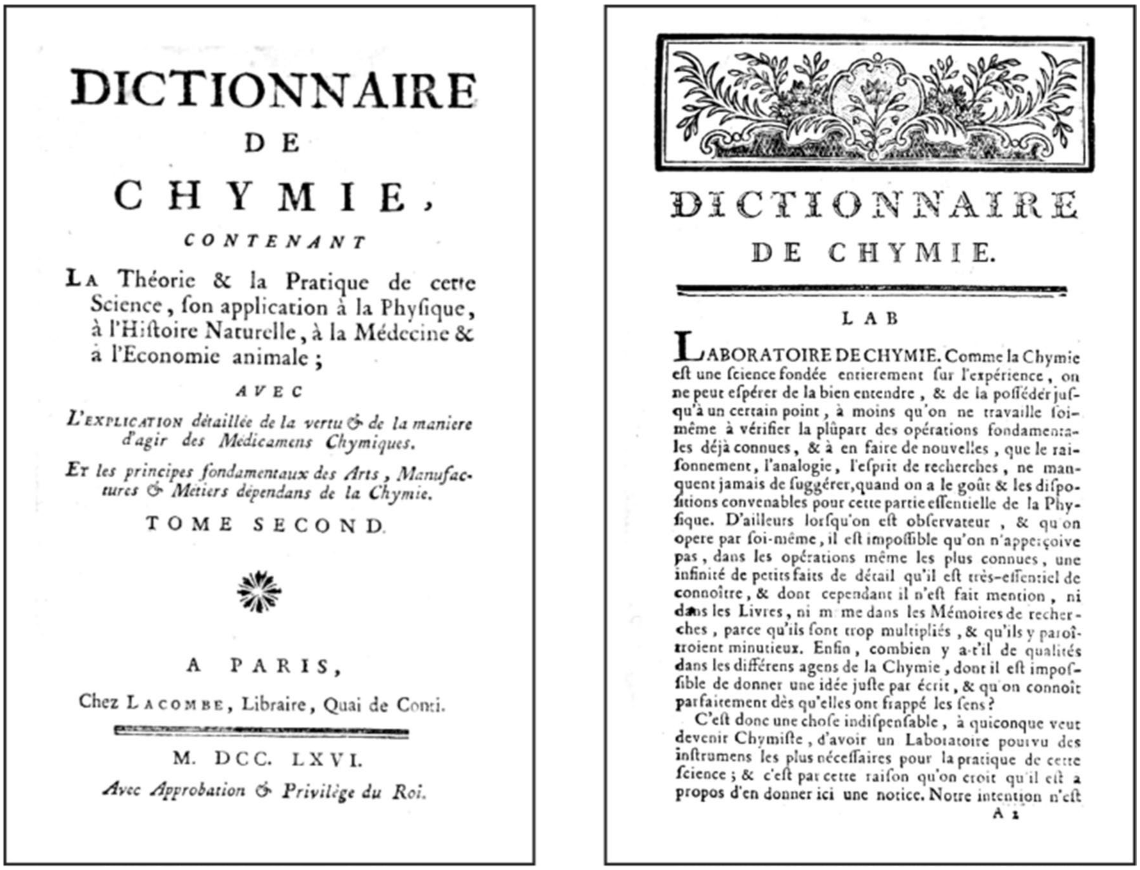


Fig. 1 **a** Title page of the book *Les Héros du travail* (1882) by the French chemist Gaston Tissandier, **b** illustration from the book showing a scene from Vauquelin's childhood. Here, the future discoverer of beryllium and chromium is being told by his teacher: "Study so you can dress like that!", **c** portrait of Louis Nicolas Vauquelin (lithograph by François-Séraphin Delpech)

perceive teachers who simply write on the blackboard and rely on textbooks as weaker than those who allow students to experiment and later discuss their experiences with them. Experimental teaching is seen by students as a "better learning opportunity."

- According to Bennett et al. [49], students see the opportunity to participate in a practical research project as an important confirmation of their desire to study chemistry.
- According to Finne et al. [39], laboratory experience, proximity and intensive communication with teachers in the laboratory environment play an important role in developing student learning through dialogue and feedback. It is therefore not surprising that student learning outcomes have declined as laboratory activities have been replaced by online activities in response to the COVID-19 pandemic.
- Loo [56] points out the difficulty of fully replicating the laboratory experience remotely. He worries that the more personal aspects of analytical instrumentation, the touch of operating an instrument and the feel of acquiring data,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DE
CHYMIE,
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LA Théorie & la Pratique de cette Science, ſon application à la Phyſique, à l'Hiſtoire Naturelle, à la Médecine & à l'Economie animale ;
AVEC
L'EXPLICATION détaillée de la vertu & de la maniere d'agir des Médicamens Chymiques.
ET les principes fondamentaux des Arts, Manufactures & Métiers dépendans de la Chymie.
TOME SECOND.
A PARIS,
Chez LACOMBE, Libraire, Quai de Conti.
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Avec Approbation & Privilège du Roi.

DICTIONNAIRE
DE CHYMIE.
LAB
LABORATOIRE DE CHYMIE. Comme la Chymie eſt une ſcience fondée entierement ſur l'expérience, on ne peut eſpérer de la bien entendre, & de la poſſéder juſqu'à un certain point, à moins qu'on ne travaille ſoi-même à vérifier la plûpart des opérations fondamentales déjà connues, & à en faire de nouvelles, que le raiſonnement, l'analogie, l'eſprit de recherches, ne manquent jamais de ſuggérer, quand on a le goût & les diſpoſitions convenables pour cette partie eſſentielle de la Phyſique. D'ailleurs lorſqu'on eſt obſervateur, & qu'on opere par ſoi-même, il eſt impoſſible qu'on n'apperçoive pas, dans les opérations même les plus connues, une infinité de petits faits de détail qu'il eſt très-eſſentiel de connoître, & dont cependant il n'eſt fait mention, ni dans les Livres, ni même dans les Mémoires de recherches, parce qu'ils ſont trop multipliés, & qu'ils y paroîtroient minutieux. Enfin, combien y a-t'il de qualités dans les différens agens de la Chymie, dont il eſt impoſſible de donner une idée juſte par écrit, & qu'on connoît parfaitement dès qu'elles ont frappé les ſens?
C'eſt donc une choſe indiſpenſable, à quiconque veut devenir Chymiſte, d'avoir un Laboratoire pourvu des inſtrumens les plus néceſſaires pour la pratique de cette ſcience ; & c'eſt par cette raiſon qu'on croit qu'il eſt à propos d'en donner ici une notice. Notre intention n'eſt
A 2

Fig. 2 Title page of the book *Dictionnaire de chymie* (1766) by the French chemist Pierre-Joseph Macquer (left), and the first page of the entry "chemical laboratory" from this book (right)

will be lost to students. In his experience, some students need the spark of operating an instrument and seeing the signal display and result first hand to ignite their attraction to analytical science.

- According to Baker and Cavinato [57], chemistry is as much about hands-on laboratory skills as it is about book knowledge. It is not possible to replicate the full laboratory experience remotely.

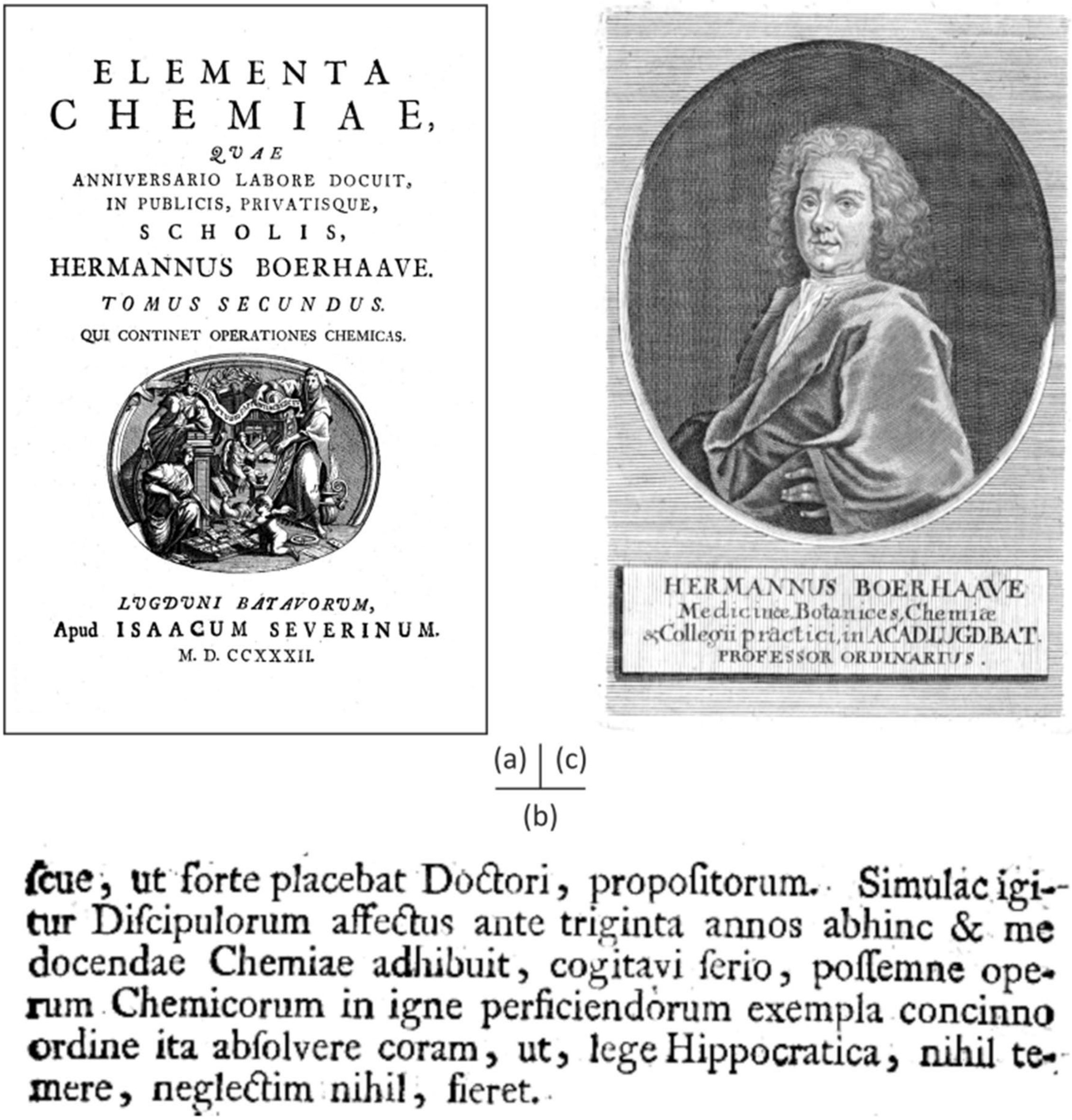
The laboratory as a space for suppressing chemophobia

According to Sutman [58], the chemistry laboratory is an important site in efforts to improve the image of chemistry. Indeed, in his critique of purely theoretical teaching, Sutman [58] points out that, "being lectured to about chemistry leaves either no impression or a negative impression of chemistry's nature, especially how its contributions are made." Conversely, an important feature of hands-on activities is their ability to improve the image of chemists. They give students "a truer and more positive appreciation of chemistry."

In his view, Sutman [58] confirms the ideas of the highly influential Dutch chemist Herman Boerhaave (1668–1738) (Fig. 3). This "communis Europae praeceptor" (instructor of all of Europe [59]) in his famous textbook *Elementa chemiae* (Fundamentals of Chemistry, 1732) writes clearly about the importance of practical chemistry teaching. He uses an allusion to the famous ancient Greek physician Hippocrates: "according to Hippocrates' Rule, nothing should be left out that was of Consequence to be known, nor any thing be added that was not necessary" [60].

In our previous communications [14, 15, 50, 61–63], we define chemophobia as a long-lasting and persistent irrational fear of chemistry and chemical substances and a strenuous effort to avoid them, leading people to become hypersensitive or even intolerant to them. We also pointed out that chemophobia, after more than 60 years of modern existence, is one of the main obstacles to the healthy development of chemistry.

In our efforts to suppress chemophobia, we see the chemistry laboratory as an inspiring place for dialogue between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QVAE
ANNIVERSARIO LABORE DOCUIT,
IN PUBLICIS, PRIVATISQUE,
SCHOLIS,
HERMANNUS BOERHAAVE.
TOMUS SECUNDUS.
QUI CONTINET OPERATIONES CHEMICAS.

LUGDUNI BATAVORUM,
Apud ISAACUM SEVERINUM.
M. D. CCXXXII.

ſcue, ut forte placebat Doctori, propoſitorum. Simulac igitur Diſcipulorum affectus ante triginta annos abhinc & me docendae Chemiae adhibuit, cogitavi ſerio, poſſemne operum Chemicorum in igne perficiendorum exempla concinno ordine ita abſolvere coram, ut, lege Hippocratica, nihil temere, neglectim nihil, fieret.

Fig. 3 **a** Title page of the book *Elementa chemiae* (1732) by the Dutch chemist Herman Boerhaave, **b** the extract on the importance of practical chemistry teaching from the book (shortened translation in text), **c** portrait of Herman Boerhaave (copper engraving by Andreas Nunzer)

the chemical and non-chemical worlds, experts and lay people, and thus a place for greater public engagement: all the more so because the laboratory is the place where the episodes in the history of chemistry are played out, the stage of human destinies and the scene of countless impressive discoveries that provide solutions to pressing problems facing humanity.

Otto Krätz [64] once pointed to the dichotomy of the laboratory. For some, it is a source of progress. For others, it is a chamber of horrors. We propose adding a third characteristic to the perception of this space. Because of its unique nature, we suggest that it be considered as a space of chemophobia suppression. It was here that the common sense of the first chemists, thanks to their diligence, tenacity and curiosity, gradually crystallised into the form of modern science. A combination of diligence (and creativity) in communicating chemistry, tenacity in counteracting chemophobic fads and curiosity about those for whom chemists work in contemporary laboratories, i.e. the general public, in a nutshell, is the solution to the problem of chemophobia. The common sense as manifested in the first chemical laboratories, based on the use of the basic human senses as a source of information, also points to the importance of a real perception of the world.

Fig. 4 Joachim von Sandrart (1606–1688): *Minerva and Saturn Protecting Art and Science from Envy and Falsehood* (oil painting 1644, Kunsthistorisches Museum, Wien)

Conclusions

Clearly, there is nothing that can create a paraphrase of chemistry and overcome it. However, the future of chemistry is threatened by the unfavourable social atmosphere created by chemophobia. Equally, the future of chemistry can be jeopardised by ill-considered actions that threaten its intrinsic quality and ability to reproduce, such as the disruption of experimental teaching. Thus, it has been shown time and again that chemists must stand up to protect the fundamental pillars of the teaching of their subject and of chemistry as a whole. They must be aware that what can be rightly taken for granted as self-evident truths must be protected. It was so in the past and it is so today. The historical perspective of this endeavour is suggested by Joachim von Sandrart's magnificent painting *Minerva and Saturn Protecting Art and Science from Envy and Falsehood* (Fig. 4). The little child (putto) at the front with the book and the ring is seen as an allegorical representation of science, and therefore of chemistry.

The only way to ensure adequate conditions for chemical research, the teaching mission of chemistry, and the sustainable development of the field in general is through a combination of the following three activities: (i) ongoing effective communication, (ii) coalition building with those who care about the future of humanity and (iii) ongoing efforts to rally support for chemistry. Laboratories and experimental education play a key role in these efforts. They provide a safe experience of real chemistry in a protected environment. They provide an opportunity to experience the democratic and inclusive nature of chemistry, open to all without distinction. They make it possible to engage in dialogue with experienced chemists–mentors, to build a chemical identity step by step and to educate new chemists.

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