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Does consulting open online educational resources to prepare for laboratory learning affect students' perception of their experimental self-efficacy and chemistry laboratory anxiety?

Valérie Camel, *[a] Jonathan Piard, [b] Isabelle Billault [c] and Marie-Noëlle Maillard [a]

Laboratory learning remains a pillar of analytical chemistry teaching, but students often arrive in the laboratory unprepared, especially being unaware of basic safety requirements or simple handling procedures. Consulting digital resources before the experimental sessions was reported to possibly improve their learning experience in the chemistry laboratory. Exploratory results suggested that it improves students' experimental self-efficacy with subsequent anxiety reduction, but there is a need for further investigating this aspect. We conducted a semi-quantitative study focusing on these two interrelated constructs in the context of chemistry laboratory teaching. Six small cohorts were considered in several teaching contexts (undergraduate and graduate) across three institutions, and students were invited to consult the open online CHIMACTIV website. When learners consult targeted resources on this website before the experimental sessions, they perceive an increase of their self-efficacy and a reduction in their anxiety in the chemistry laboratory. For self-efficacy, a higher effect was observed on the "understanding concepts" dimension, followed by the dimension "sufficiency of resources". For anxiety, a higher benefit was noted for the dimension "using equipment and procedures" followed by "collecting data". Comparable results were obtained across the different cohorts. The correlation coefficients between dimensions confirm a positive and significant relationship: reductions in chemistry laboratory anxiety are associated with increases in experimental self-efficacy. The strongest correlation was observed between the anxiety dimension "using equipment and procedures" and the self-efficacy dimension "sufficiency of resources." These results suggest that students perceive online resources, such as the CHIMACTIV website, as contributing to their chemistry learning, particularly in relation to their self-efficacy and anxiety in laboratory contexts.

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Introduction

"Analytical chemistry can be defined as the chemical metrological discipline that develops (R&D), optimizes, and uses tools and measurement processes in order to strengthen its capabilities to extract information – particularly to obtain quality (bio)chemical information about objects and systems of natural/artificial nature in order to fulfil specific needs or requirements with a view of facilitating grounded, timely decisions in scientific, technological, economic, and social areas" (Valcárcel, 2016, p. 15). In practice, this sub-discipline of chemistry is of crucial importance to other disciplines. However, time devoted to courses in analytical chemistry has been reduced in many universities, as recently exemplified in Sweden (Bergquist *et al.*, 2023). Besides adapting to shorter courses, teaching analytical chemistry faces other challenges: learners must acquire knowledge and understanding of analytical techniques and instrumentation, as well as the ability to process and interpret data acquired with different analytical methods (Masania *et al.*, 2018). Laboratory instruction may promote the learning of certain theoretical concepts, and it is also very important in analytical chemistry to acquire practical skills (Hofstein, 2004). Laboratory sessions are also the best way to train students in the application of experimental procedures, the development of protocols and experimental methods, and the scientific approach (critical analysis, interpretation of results, scientific argumentation based on evidence), with a

[a] *UMR SayFood, Université Paris-Saclay, INRAe, AgroParisTech, 22 place de l'agronomie, 91120 Palaiseau, France. E-mail: valerie.camel@agroparistech.fr*
[b] *Université Paris-Saclay, ENS Paris-Saclay, PPSM, CNRS, 4 avenue des sciences, 91190 Gif-sur-Yvette, France*
[c] *Université Paris-Saclay, CNRS, Institut de Chimie Physique UMR 8000, 91405 Orsay, France*

wide diversity of teacher instructions and tasks proposed to students depending on the learning objectives assigned to laboratory activities (Hofstein and Mamlok-Naaman, 2007). As underlined by Agustian and Seery (2017, p. 518), ''laboratory education forms a unique and integral component of the chemistry curriculum''.

Indeed, the laboratory offers a ''more informal atmosphere and opportunities for more interaction among students and their teacher and peers can promote positive social interactions and a healthy learning environment conducive to meaningful inquiry and collaborative learning'' (Hofstein and Lunetta, 2004, p. 36). However, it has been suggested that ''meaningful learning in the laboratory would occur if students were given sufficient time and opportunities for interaction and reflection'' (Hofstein and Lunetta, 2004, p. 32). Yet, the time devoted to lab sessions in several curricula has decreased in recent years, mainly due to the associated costs, the lack of preparation time as well as stricter safety regulations (Boesdorfer and Livermore, 2018; Chalupa and Nesmerak, 2023). In the meantime, unprepared students arriving in the laboratory often suffer from cognitive overload (as laboratory is considered a complex learning environment); this leads to task execution as ''cookbook'' following the laboratory guide, without making connections between experimental work and the theoretical concepts (Jolley *et al.*, 2016). In addition, unprepared students may present a low self-efficacy belief and/or some anxiety relative to the chemistry lab (especially if they have minor previous laboratory experience due to an unfamiliar learning environment, handling of chemical hazards and expensive instruments, as well as acquisition of data within a limited time frame), both of which hinder learning. Thus, a recent study reported that students' anxiety decreases after having experienced chemistry laboratory, possibly due to the development of security and self-confidence in manipulating hazardous chemicals, using equipment, executing laboratory procedures, collecting data and managing their time in the laboratory (Avila-Ascanio and Gualdron-Pinto, 2022).

In such a context, particular attention should be paid to the educational content and activities offered to students in order to prepare them for chemistry laboratory classes. As recently reviewed, several pre-laboratory activities have been proposed in chemistry curricula to improve laboratory learning experience (Agustian and Seery, 2017). Such activities differ depending on their learning objectives: (i) mainly lectures, quizzes and discussion to introduce chemical concepts; (ii) technique videos, interactive simulations, mental preparation (related to the experiments) or safety information to introduce laboratory techniques; (iii) the pre-cited activities for addressing affective dimensions that are important during the laboratory sessions (namely student confidence and motivation).

In the past decade, the introduction of digital tools (videos, simulations, online quizzes, virtual lab, *etc.*) permitted the production of a broad coverage of resources in chemistry. Efforts have been put on addressing the engaging character of these resources, in order to favor their use by the students for learning. As an illustration, online interactive tools were reported to be freely chosen by the majority of 252 first-year students enrolled in a general chemistry laboratory course in a Uruguayan public university (Veiga *et al.*, 2019). In the same line, in the context of an analytical chemistry course in the second year of an Australian university, students' attitudes were reported to be very positive toward online material (especially prelab quizzes) since digital resources provide a ''flexible learning platform'' that enables students to work independently and at their own pace (Jolley *et al.*, 2016).

Yet, whether such digital resources have a beneficial impact on learning by enhancing experimental self-efficacy and reducing chemistry laboratory anxiety has been rarely explored until now. In particular, in the field of analytical chemistry where three major open educational websites are currently available (the ChemCollective site – https://chemcollective.org/, the Analytical Sciences Digital Library – https://asdlib.org/, and our CHIMACTIV website – https://chimactiv.agroparistech.fr/en), there is a lack of studies assessing the benefit of using these open online educational resources as support for pre-laboratory activities in order to improve students' self-efficacy and reduce their anxiety, with a view of favouring learning in chemistry laboratories. Since, from our point of view, CHIMACTIV is the sole website that offers broad coverage of the analytical chemistry field and bilingual resources, this website will serve as a model to evaluate this benefit.

Discussion of the literature

Laboratory work as a pillar of analytical chemistry education

Experimental sessions are recognized as important for teaching chemistry. ''Doing science in the chemistry laboratory is highlighted as a key characteristic of laboratory work that distinguishes it from other pedagogies in higher education, such as lectures and tutorials. It largely defines a chemist and, as such, is deeply ingrained in their professional identity.'' (Agustian, 2025, p. 218). As a consequence, the American Chemical Society international guidelines for undergraduate chemistry programs ''require that students have 350 h of lab experiences beyond general (or introductory) chemistry''; in addition, these guidelines recommend ''that the majority of these lab activities occur in person'' to ensure students get the required experience and skills (Brooks and Lawal, 2025, p. 379).

Several learning objectives may be assigned to these sessions as mentioned previously, such as a better understanding of the theoretical concepts, acquiring practical skills and/or scientific skills (such as obtaining data and being faced with variability of measurements), or developing transferable skills (such as teamwork, team management or problem-solving) (Seery, 2020; Agustian *et al.*, 2022). A progressive laboratory curriculum is recommended across the entire degree (first-year to fifth-year of university) so that practical and cognitive tasks are more demanding as the students pass a new year, and the affective domain (such as self-efficacy and laboratory anxiety) deserves also consideration (Agustian, 2025).

Classically in chemistry education four laboratory instruction styles have been proposed: expository, open inquiry (or inquiry), guided inquiry (or discovery) and problem-based (Domin, 1999). They all differ considering the outcome, approach and procedure. Expository, guided inquiry, and problem-based activities all have predetermined outcomes, while outcomes are undetermined with open inquiry-based activities. Considering the approach, expository and problem-based activities typically follow a deductive approach (students apply a general principle toward understanding a specific phenomenon), while guided inquiry and open inquiry-based activities are inductive (by observing particular instances, students derive the general principle). For the procedure to be followed in the laboratory, it is either provided to the students (expository and guided inquiry-based activities) or designed by the students themselves (open inquiry and problem-based activities). A more detailed characterization was proposed a few years later, with five levels of inquiry based on six characteristics (problem/question, theory/background, procedures/design, results analysis, results communication, conclusions) and the level of student independence associated with each: confirmation, structured inquiry, guided inquiry, open inquiry and authentic inquiry (Buck *et al.*, 2008). The laboratory offers a unique opportunity for learning by inquiry (Hofstein and Lunetta, 2004).

Several authors report a beneficial of inquiry-based instruction modes for chemistry learning in high education. As an illustration, in a mixed-methods (questionnaire plus interviews) research study, Matakaa and Kowalske (2015) reported that undergraduate students who participated in problem-based learning laboratory units improved their self-efficacy belief in chemistry, and that this improvement was stable and long-lasting. In the field of analytical chemistry education, Madybekova *et al.* (2026) reported that, besides enhancing competency development, problem-based learning (with guided-inquiry tasks for the lab work) positively influenced students' attitudes toward analytical chemistry.

However, inquiry-based activities are time-consuming, and this time may not be available in chemistry curricula (Ural, 2016). In addition, as underlined by Bruck and Towns (2009) "underprepared students have experienced negative results when attempting inquiry-based activities"; these authors recommended that "students must possess appropriate prior knowledge of the topic to be investigated in laboratory" and that they "must also possess sufficient knowledge of the procedures and techniques for the laboratory and be able to use them".

In the case of analytical chemistry education, experimental sessions are important since "the ability to make reliable and accurate measurements by using the analytical method is an essential part of the undergraduate curriculum" (American Chemical Society, n.d.). As a consequence, teachers "should consider how to effectively combine classroom and laboratory instruction to meet learning goals" (Kovarik, 2025). However, laboratory sessions may be in practice difficult to implement in the academic programs for high level degrees (such as master of science), as several required instruments may be unavailable or operational (*e.g.* liquid chromatography) due to instrument cost, failure or obsolescence. Indeed, obtaining and maintaining instrumentation was the challenge most identified by 322 instructors of undergraduate analytical chemistry surveyed in 2021 under the auspices of the Division of Analytical Chemistry of the American Chemical Society (Kovarik, 2025). When laboratory sessions are proposed, their duration in the curricula remains limited due to expensive costs as compared to digital tool alternatives (Achuthan and Murali, 2015; Kennepohl, 2021), with time spent in chemistry laboratories decreasing over years (Reid and Shah, 2007). Indeed "teaching laboratories are labor intensive (prep staff, instructional faculty, graduate teaching assistants) and costly (specialized classroom space, breakable equipment, instrumentation, consumable chemicals that cannot be reused each semester, waste disposal costs, salaries and tuition of graduate student instructors...). And these costs only increase as we move from introductory laboratory courses for the masses to specialized laboratory courses for the (relatively) small number of chemistry majors." (Bretz, 2019, p. 194).

By way of consequence, the learning objectives of these laboratory sessions should be carefully assigned. In addition, preparation of these sessions is mandatory since "the value of laboratory work must be severely limited by the students' unpreparedness" (Reid and Shah, 2007, p. 177), especially for students who have limited experience in chemistry laboratory. For that purpose, digital resources have faced growing interest in recent years, especially since the Covid-19 pandemic, as they offer interactive formats that sound promising as detailed below.

Preparing for lab sessions with interactive digital resources

Providing theory and procedural guidance in an interactive way using digital resources should be helpful to students, avoiding high cognitive load upon arrival in the chemistry laboratory (Washbourn, 2024). That way students should be more performant in the laboratory. In addition, preparing lab sessions is also intended to enable students to feel more confident about lab work and/or to reduce students' anxiety once in the chemistry laboratory (Teo *et al.*, 2014; Agustian and Seery, 2017). In particular, in analytical chemistry education, the use of e-quizzes combined with instructional videos for preparing lab sessions was reported to increase the students' feeling of preparedness and to obtain a positive learning experience from the laboratories (Jolley *et al.*, 2016). Instructional videos were also found to be successful for upper-division chemistry laboratory courses characterized by an instrument intensive nature of the experiments: students watched the videos to become more prepared for the lab sessions, with subsequent gain in autonomy as they acquired more familiarity with the instruments (Schmidt-McCormack *et al.*, 2017). The use of a virtual laboratory experiment coordinated with practical laboratory assignments in a blended learning scenario was also found as a valuable teaching and student engagement tool (Bortnik *et al.*, 2017).

It was also reported significantly less technique incidents in the lab when students prepared the session with online digital resources as compared to prelab preparation using a traditional laboratory script, as well as an improvement in manipulations; this was aligned with students feeling more confident in attempting to conduct activities in the lab when they had used the online learning resource as a preparative tool (Sarmouk *et al.*, 2019).

In another study within the context of *Bachelor of Science*, Kolil *et al.* (2020) reported that most students surveyed (a total of 1225 students) expressed low or below average self-efficacy scores before performing experiments in chemistry lab sessions. They also gave evidence that the use of simulations and animations (thanks to a dedicated virtual laboratory platform) significantly improved the experimental self-efficacy of their students.

Interestingly, Soulé *et al.* (2025) have recently reported the beneficial use of a virtual lab as a teaching material optional for 168 first-year students enrolled in a chemistry introductory course to prepare experimental sessions; 162 (96.4%) students declared having used the platform. Among users, "a significant majority (>80%) reported that the platform helped them become familiar with the lab and reduced their anxiety about the laboratory course" (Soulé *et al.*, 2025, p. 351). This virtual lab, ChemView360, was based on 360° pictures of the laboratory with interactive markers on hot spots and also short videos highlighting the experimental procedures and outcomes.

In another study, Gungor *et al.* (2022) tested the impact of virtual reality (VR) on self-efficacy, interest, self-concept and laboratory anxiety of 17 undergraduate (2nd and 3rd year) pharmacy students from a northern European university, enrolled in a three-week organic chemistry course (organized with two weeks of theoretical courses followed by one week of laboratory sessions). After collecting students' feedbacks thanks to a questionnaire exploring the four constructs completed by semi-structured interviews, at the end of a course combining VR and lab sessions, they noted that some "students reported an increase in positive association confidence in the lab, and a decrease in laboratory anxiety" (Gungor *et al.*, 2022, p. 5), possibly linked to preparation of lab sessions using VR.

Consequently, several studies report the beneficial impact of preparing chemical laboratory sessions upon consulting digital resources. These exploratory results suggest enhancement of students' experimental self-efficacy with subsequent anxiety reduction as detailed above. For example, Dalgarno *et al.* (2012) reported that undergraduate chemistry students who used a virtual laboratory for preparing chemistry laboratory sessions were generally positive about its value in contributing to their confidence and reducing their anxiety about practical work.

Yet, there is a need of further investigating this aspect, and this is the focus of our study, which aims to assess the positive impact of consulting targeted digital resources in preparation of practical work on enhancing self-efficacy and reducing anxiety.

The CHIMACTIV website as a support for chemistry learning

We decided to provide students with appropriate assets related to analytical chemistry, so that they have the opportunity to train themselves before the laboratory sessions. Thus, a few years ago, we created the CHIMACTIV website. It provides open interactive digital resources to support chemistry learning in both laboratory and theoretical contexts (Camel *et al.*, 2020); all these resources are under the international Creative Common license BY-NC-ND (Attribution-NonCommercial-NoDerivatives) 4.0. The website content spans four main areas: chemistry concepts, methodology, laboratory techniques, and safety considerations. The resources include videos (text transcripts with timelines are available as recommended by Schmidt-McCormack *et al.*, 2017), interactive diagrams, quizzes, games and exercises designed to engage students, reduce cognitive load, and facilitate learning before, during, and after laboratory sessions. Their open access and digital responsiveness make them easily available on any medium (computer, tablet, or smartphone), providing "easy-to-access" information. This feature is particularly convenient for enabling consultation out-of-class in remote environments (such as transports) as well as in-class in chemistry labs; it was previously reported to be valuable for third-year chemistry students, who actively watched lab videos during lab sessions when they were viewable on a portable electronic device, to gain assistance for using advanced chemical laboratory techniques and instrumentation (Loughlin and Cresswell, 2021). Teachers may easily direct their students to targeted CHIMACTIV resources, particularly before experimental sessions, so that they can review safety requirements (Camel *et al.*, 2021), familiarise themselves with the procedures to be used, and reflect on the experimental plan to be implemented. Such resources are particularly useful for teachers who intend to flip their laboratory sessions as key concepts related to analytical chemistry are covered and pre-laboratory activities are easily designed by targeting the corresponding resources.

By integrating multiple modalities of learning, the CHIMACTIV resources aim to promote active engagement, self-directed preparation, and a deeper understanding of experimental procedures. Such tools align with research showing that pre-laboratory preparation and interactive resources can enhance students' self-efficacy, reduce anxiety, and improve overall engagement in laboratory learning (Agustian and Seery, 2017).

Theoretical framework

"Distractions and risks may increase anxiety, which can reduce efficacy through thoughts of failure, physiological manifestations of stress, and the reduction of coping mechanisms" (Gist and Mitchell, 1992, p. 194). It is now well documented that, in chemistry education, students may develop anxiety towards laboratory sessions due to several factors, such as handling chemicals, using unfamiliar and expensive equipment, improper experimentation, lack of concept understanding or lack of knowledge related to safety procedures (Kolil *et al.* 2020; Gungor *et al.*, 2022). The limited duration of the experimental sessions also contributes to their anxiety, as they often fear that they will not have enough time to complete their experiments.

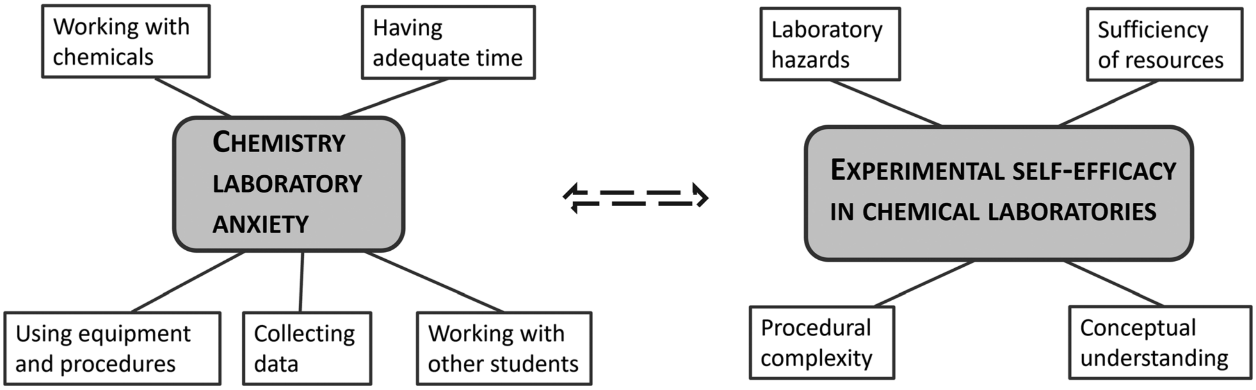

Fig. 1 The theoretical framework considered in this work.

Whenever present, this chemistry laboratory anxiety will negatively affect students' experimental self-efficacy during lab sessions, with possible adverse impacts on learning and performance. The theoretical framework used in this study is illustrated in Fig. 1 and detailed below.

Experimental self-efficacy

Self-efficacy was introduced as an important concept by Bandura (1977). It may be defined as "a person's judgement of their ability to organise and use the various activities necessary to accomplish a task" (Bouffard-Bouchard and Pinard, 1988, p. 411). This judgement, highly dependent on the situation and its context, is well-recognized as an important determinant of academic outcomes, since it is described as "the beliefs of individuals about their abilities to successfully complete an action" (Kolil *et al.*, 2020, p. 350). Self-efficacy is considered a dynamic construct, since the person's judgement to perform efficiently a specific task may change over time, especially as "new information and experience are acquired" (Gist and Mitchell, 1992, p. 184).

Science self-efficacy was found to positively predict science achievement at both student- and classroom-levels (Burns *et al.*, 2021). As self-efficacy is dependent on the domain considered (Artino, Jr, 2012), we focused our bibliographic research on applications of this construct to chemistry teaching, focusing on teaching with experimental sessions as students' self-efficacy beliefs might be different in lab sessions or during theoretical courses. We were particularly interested in investigating "experimental self-efficacy", previously defined as "the belief in one's ability to successfully execute action and observation in a controlled way within an experimental environment to achieve its outcomes" (Kolil *et al.*, 2020, p. 3).

We found only two questionnaires detailed in the literature and already validated for exploring self-efficacy belief in the context of chemistry learning during experimental sessions. The first one was developed and validated by Alkan (2016) for high school students in Ankara (Turkey), and with two dimensions considered (psychomotor and cognitive self-efficacy), each being explored through 7 questions.

The second questionnaire was developed and validated by Kolil *et al.* (2020) in a teaching context rather close to ours, since they considered undergraduate students (1225 in total) from different institutions (in India) where laboratory classes were part of the chemistry teaching programs. They identified factors causing anxiety related to chemistry laboratory based on an open-ended online survey sent to all students, and they further validated the four proposed main categories thanks to a survey conducted amongst 125 students (in a *Bachelor of Science* program) with a set of four typical experiments (such as acid–base titration). Then they developed questions related to each factor, that were verified by experts from chemistry as well as educational psychology. Their final questionnaire includes four dimensions: conceptual understanding (it refers to the student's knowledge of the theory behind the experiments, and includes the understanding of the concepts and principles being tested in the experiments), procedural complexity (this is related to the difficulties faced by students in calculating arithmetically, for example for preparing diluted solutions, as well as in executing the experiment steps, and it includes the understanding of the required calculations and steps), laboratory hazards (it is related to potential accidents such as accidentally breaking apparatus or spilling chemicals), sufficiency of resources (it refers to the adequacy of apparatus such as beakers or pipettes, instruments such as flame photometer, and instructors to perform the experiments) (Kolil *et al.*, 2023). The first two dimensions refer to cognitive laboratory activities and the last two to physical laboratory activities (Kolil *et al.*, 2020; Kolil *et al.*, 2023). Each of these four dimensions was explored with three questions, thus leading to the "Experimental self-efficacy (ESE)" questionnaire composed of 12 items. This ESE questionnaire was further tested and revalidated by Kolil *et al.* (2023) on 1123 students from chemistry, physics and biology over 26 institutions in India using confirmatory factor analysis.

We decided to choose the ESE questionnaire for assessing our students' chemistry laboratory self-efficacy belief, due to the high level of similarity with our context.

Chemistry laboratory anxiety

Anxiety may be defined as "an unpleasant (usually temporary) emotional state characterised by feelings of tension, apprehension, nervousness and worry" (Hellemans, 2004, p. 2). An anxious student "will be more easily distracted, suffer from negative cognitive interference, and this state could have a negative impact on the academic performance'' (Danthony, 2020, p. 14).

It is well-documented that most students are anxious once in the laboratory since they are not very familiar with this environment. This is particularly crucial for chemical laboratory due to the use of chemicals and the presence of several hazards, as well as other disturbances such as noise and smells (Stone and Arenas, 2026). As an illustration, 43 undergraduate students (out of 55) enrolled in a Chemistry program in an Australian university declared feeling anxious about the laboratory sessions (Dalgarno *et al.*, 2012). The limited time devoted to lab sessions is also a major factor of anxiety for students since they are afraid of not being able to perform the experiments and acquire their data (Sharpe, 2012). The cognitive tasks associated with lab sessions are also a major source of anxiety for students (Sharpe, 2012; Rummey *et al.*, 2019).

Several questionnaires exploring anxiety related to chemistry laboratory were reported in the literature, with few of them being readily available.

The Laboratory Anxiety Questionnaire (LAQ) was developed for undergraduate students in a Turkish university (Acar Sesen and Mutlu, 2014). It is composed of 20 items covering four aspects of experimental work (using chemicals, laboratory materials and equipment, laboratory accidents, and making mistakes during the experiment process). An adaptation was reported and tested with students from a *Bachelor of Science* in Food Technology, that is composed of 20 items covering the same aspects (handling chemicals, laboratory materials and equipment, laboratory accidents, and committing mistakes during the experiment) (Damo *et al.*, 2020). The items are formulated as statements rather than questions, and they are mainly concerned with lab hazards.

The Chemistry Laboratory Anxiety Instrument (CLAI), also cited as the Chemistry Laboratory Anxiety Scale (CLAS), was developed for measuring college students' anxieties in chemistry laboratories in the United States (Bowen, 1999). It is composed of five dimensions (working with chemicals, using equipment and procedures, collecting data, working with other students, and having adequate time) explored by means of 20 questions in total (4 items per dimension). Thus, it measures several sources of anxiety in chemistry laboratories rather than overall anxiety. This instrument has been validated using factor analysis. Interestingly it explores a dimension related to collaborative work that is frequently put in place in analytical chemistry laboratories due to limited access to instruments and to favour pair interactions.

The CLAI questionnaire was recently implemented with additional questions referent to practical work that may affect chemistry laboratory anxiety (*i.e.* asking for help from a demonstrator, interpreting the data and answering assessed questions) as well as questions relative to chemistry laboratory self-efficacy for each aspect of the laboratory work considered for anxiety, resulting in the CLASEQ questionnaire (Rummey *et al.*, 2019). It was tested in 2017 with 1st-year university students enrolled in a chemistry unit at an Australian university at the start and end of semester one, and at the start of semester two: as a trend ''students reported lower anxiety about the social aspects of laboratory work than about the practical tasks, and lower anxiety about the practical tasks than the cognitive tasks'' (Rummey *et al.*, 2019, p. 91), and the opposite was true for self-efficacy. Hence, students were most anxious about the laboratory aspects that most directly impact their final grades, and completing the work on time was the aspect of laboratory work that students had the lowest self-efficacy about. However, since the resulting CLASEQ questionnaire was not thoroughly validated *via* a factor analysis, we decided not to use it in this work.

Thus, the CLAI questionnaire was retained in our study. It is intended to enable comparison of different instructional approaches used to teach in chemistry laboratories. Our concern to integrate digital resources before or in-between lab sessions may be considered as flip teaching, so that this approach might be assessed with this instrument. In addition, the CLAI questionnaire was used with some minor modifications by several authors in previous studies under undergraduate and graduate contexts quite similar to ours, and interesting data were collected (Kurbanoglu and Akim, 2010). The original CLAI questionnaire in English was also translated into Turkish as well as into Spanish for its use in, respectively, Turkey (Kurbanoglu and Akim, 2010; Ural, 2016; Alkan and Koyuncu, 2017; Aydogdu, 2017; Alkan, 2021) and Latin America (Avila-Ascanio and Gualdron-Pinto, 2022).

Interrelation between these two constructs

Anxiety is generally admitted as a factor that influences self-efficacy, and anxiety has been reported to be negatively associated with self-efficacy, especially in the field of science. For example, it was reported that chemistry laboratory anxiety (addressed using the CLAI questionnaire) was correlated negatively to self-efficacy (addressed using the Motivated Strategies for Learning Questionnaire), and that self-efficacy predicted chemistry laboratory anxiety in a negative way (Kurbanoglu and Akim, 2010); findings were reported for 395 undergraduate chemistry students in Turkey. Similarly, for near 150 first-year students in Australia, an inverse correlation was observed between chemistry laboratory self-efficacy and chemistry laboratory anxiety for each of the same aspects of laboratory work (Spearman's rho correlation values in the range -0.428 to -0.656 with p-values < 0.05) (Rummer *et al.*, 2019). Also, it was reported that high school students ''who have anxiety about working with chemicals and tools in chemistry laboratory have low psychomotor self-efficacy beliefs'' (Alkan, 2021, p. 35).

On the other hand, it seems that ''self-efficacy does not play a significant role in anxiety'' (Trisnaningati, 2021, p. 6727). In the meantime, anxiety and self-efficacy are likely to dynamically interact, so that a ''dual intervention'' approach, focusing on increasing self-efficacy and decreasing anxiety is recommended (Burns *et al.*, 2021).

In this work, we aimed at investigating if the use of the CHIMACTIV resources for the preparation of chemistry lab sessions has a positive impact on these two constructs simultaneously.

Objective of the study

In this study, we attempted to assess more precisely the impact of consulting targeted open online CHIMACTIV resources as pre-laboratory activities on students' perception of their experimental self-efficacy and anxiety in the context of chemistry laboratory teaching. An additional objective was to confirm the correlation between experimental self-efficacy and chemistry laboratory anxiety, and to explore the interrelations between their dimensions to gain a more nuanced understanding.

Our work was guided by the following research questions:

RQ1 – *Does consulting online resources (with more or less guidance) prior to practical sessions have an impact on students' sense of self-efficacy in successfully completing their practical sessions (experimental self-efficacy)?*

RQ2 – *To what extent these open online resources used for pre-laboratory activities influence students' perception of their anxiety when undertaking practical training in the chemistry laboratory (chemistry laboratory anxiety)?*

RQ3 – *Is there a correlation between these two constructs, and between their respective subscale dimensions?*

Methods

Instrument for collecting data

Students' perception was assessed using an anonymous online (Google form) single questionnaire containing three sections with a total of 41 questions.

The first section aimed at collecting information on our students' profiles, including gender, current academic program and previous academic background, as well as their usage (or not) of the CHIMACTIV website (7 questions) (see SI, Table A1). Students were asked how frequently they consulted the CHIMACTIV website (options: once, 2–5 times, 6–10 times, 11 times or more) and the average time they spent on these resources per consultation (options: <2 min, 2–5 min, 5–15 min, 15–30 min, 30 min–1 h, >1 h) during the program or the teaching activity.

Then the questionnaire was further composed of 32 items in total: 12 questions assessing experimental self-efficacy (modified ESE exploring the four dimensions "conceptual understanding", "laboratory hazards", "procedural complexity" and "sufficiency of resources", with three items per dimension) and 20 questions assessing chemistry laboratory anxiety (modified CLAI exploring the five dimensions "working with chemicals", "using equipment and procedures", "collecting data", "working with other students", and "having enough time" with four items for each dimension), all rated on a 5-point Likert type scale (choices: totally disagree 1 – 2 – 3 – 4 – 5 totally agree). At the top of the modified ESE section, a definition of chemistry laboratory self-efficacy was provided (see SI, Table A2) to help students better understand the topics addressed. Similarly, for the anxiety section, a definition of chemistry laboratory anxiety was also provided at the beginning of this section (see SI, Table A3) to clarify the construct being measured.

To avoid assessing the impact of consultation of any available digital resource, we made changes to the initial wording of the questions of the original ESE and CLAI questionnaires, in order to systematically inquire about the perceived positive effect of consulting the CHIMACTIV resources on the item being assessed. Then, to ensure correct understanding by our students, French translation was performed by the co-authors of this article (who are teachers in chemistry) with the aid of the online Deepl website where back translation was systematically included (see Tables A2 and A3 in the SI).

Participants, teaching contexts and administration of the questionnaire

As students' experience in the chemistry laboratory may depend on several factors within and across institutions (such as the collaborative character of the tasks, the variety of the activities, the students' backgrounds as well as interactions with their teachers), we have considered several educational contexts (teacher training college, university, and an engineering school) in order to increase the scope of our results. A total of six cohorts were included in this study (125 students; among them 30 undergraduate and the others graduate). Details of the programs and profiles of the students for each cohort are given in Table 1. Interestingly, for three cohorts the students were mainly chemists, for two other cohorts they were mainly biochemists, and for the last cohort, they were mainly biologists. We may hypothesise that biologists (and possibly biochemists) would have different attitudes towards analytical chemistry than chemists; if so, possible cohort effects could be anticipated in our results.

During their course, students were oriented by their teacher towards the consultation of specific resources of the CHIMACTIV website in order to prepare the experimental sessions as illustrated in Fig. 2. Self-consultation of these resources was advisable for the students of all cohorts considered, in order to prepare for lab sessions. From our practice it seems that targeting the resources to be consulted by the students, with their corresponding direct links (URL links), in line with the forthcoming lab sessions is helpful for the students. Then presenting orally the recommendations of consulting the resources with the expected benefits for the students, coupled with detailing these recommendations on a paper or an online page of the learning management system (such as the Moodle course) is fruitful.

The resources to consult varied depending on the educational context, in particularly the initial background of the students as well as the experiments planned during the lab sessions (details are given in SI, Table A4). In the particular case of cohort 3, students were asked to complete an online quiz embedded in an H5P activity module within Moodle called 'Interactive Content'. This activity, entitled "How to succeed in your practical sessions on "Chromatography, detection and quantitative analysis"" aimed to prepare students for key steps in their practical sessions; it was published online

Table 1 Details of the cohorts considered in this work (total number of students: 125; total number of respondents: 99; total number of respondents using CHIMACTIV and considered in this work: 89)

Cohort code	Faculty of the Université Paris-Saclay operating the course	Level of the students	Profile of the students	Period of collecting the data	Academic program	Enrolled course	Number of students in the cohort	Rate of respondents to the questionnaire (%)	Rate of CHIMACTIV users among respondents
1	ENS Paris-Saclay (pre-service teacher college)	Undergraduate (third-year of bachelor)	Future scientists (chemists)	June 2023	Chemistry	Analytical chemistry	30	43.3	88.2
2		Graduate (second-year of master)	Future teachers (chemists)	June 2024	Teacher training	Preparation of lectures and practical work	14	42.9	85.7
3	UFR Sciences (university)	Graduate (first-year of master)	Future scientists (chemists)	March–April 2024	Chemistry	Analytical chemistry	25	80.0	100.0
4	AgroParisTech (engineering school)	Graduate (first-year of master)	Future scientists (biochemists)	April 2023	Nutrition and Food Sciences	Experimental workshops	17	100.0	94.1
5		Graduate (first-year of master)	Future scientists (biochemists)	May 2024	Nutrition and Food Sciences	Experimental workshops	22	100.0	83.4
6		Graduate (second-year of master)	Future engineers (biologists)	October 2023	Chemical risk analysis	Environmental contaminants	17	94.1	93.8

approximately one month before the lab sessions. This activity was not marked and could even be attempted several times to achieve the highest possible score. Failure to complete this activity did not result in a penalty and did not prevent students from accessing the practical sessions.

The laboratory instruction style varied (structured-inquiry or expository, and guided-inquiry or problem-based) depending on the educational context as detailed in Table 2. As in expository instruction lab understanding is mainly developed outside of the lab, thanks to post-lab activities (Domin, 2007), in such a teaching scenario for cohort 6 post-lab sessions were scheduled that were dedicated to data treatment and interpretation thanks to targeted bibliography analysis.

At the end of the course, students of the considered cohort received the link towards the online questionnaire containing all the questions and definitions of the constructs concerned (except for cohort 2: the link was sent at the end of the year). The 100% response rate at AgroParisTech could be explained by the mode of administration (the questionnaire was completed in person at the end of a teaching session in the presence of instructors, which ensured immediate participation), as well as the fact that in this institution students are accustomed to feedback practices. No specific incentive structures were implemented in either case.

Filling the questionnaire was optional for the students, and no extra mark was delivered for that. The collected responses were anonymous. Consents were obtained from the students to participate in this study, and the study was conducted in line with ethical guidelines of the three institutions concerned (AgroParisTech, ENS Paris-Saclay and UFR Sciences from the Université Paris-Saclay).

Data treatment

Once the data had been collected (99 respondents in total), students who claimed they did not use the CHIMACTIV website during the concerned course were removed, since our aim was to assess the impact of using these resources on preparing students for lab sessions, focusing on chemistry lab anxiety and self-efficacy. Students who did not use the resources to prepare for the laboratory sessions argued that they did not need them or had not been informed about them.

Finally, data were retained from 89 respondents. Then two types of treatment were performed. First, data were treated as ordinal to obtain the percentage in agreement with each item (calculated using those responding "4" or "5"). Then data were treated as numerical values to facilitate their compilation. In particular, the values were added up for all questions relating to the same dimension before being normalised according to the number of questions. A semi-quantitative analysis was carried out by determining the averages for each of the dimensions of anxiety and self-efficacy.

Cronbach's alpha values were determined to verify the internal consistency of the responses, with satisfactory ranges when gathering the data collected for all students as shown in Table 3 (overall range 0.85–0.94 and 0.78–0.85, respectively, for anxiety and self-efficacy). Considering each cohort separately,

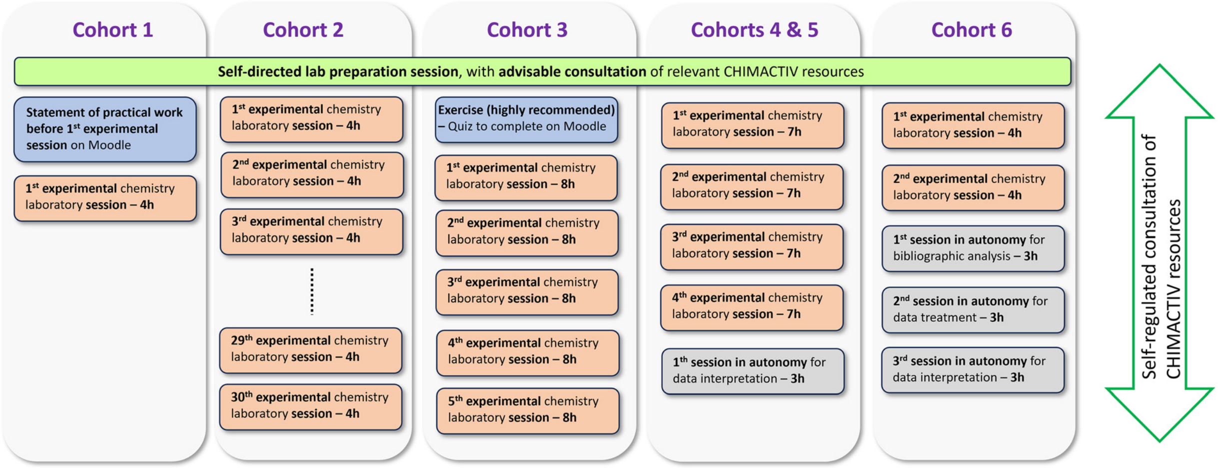

Fig. 2 Teaching contexts and scenarios for using the CHIMACTIV resources to prepare experimental sessions in our study – the chemical laboratory sessions are highlighted in orange color, while homework for preparation is indicated in green color. The additional use of Moodle is underlined by the blue color, and post-lab sessions in autonomy scheduled in students' timetable are indicated in grey color. *Consultation of the CHIMACTIV website was also possible during the lab sessions and after these sessions*.

all Cronbach' alpha values were acceptable for all dimensions of anxiety. Results were quite satisfactory also when considering data relative to self-efficacy, despite three low values (range 0.50–0.60). However, one value remained clearly unacceptable (below 0.50) for self-efficacy in the case of cohort 1; as a consequence, data collected for this cohort were not retained for exploring this construct here.

Total scores per student for each construct (anxiety or self-efficacy) were also considered. Kolil *et al.* (2020) analysed the total individual scores collected with their 12-item ESE questionnaire with a 5-point Likert type scale upon the following classification: 12 to 23 points (low self-efficacy), 24 to 35 points (below average self-efficacy), 36 to 47 points (above average self-efficacy), 48 to 60 points (high self-efficacy). Results for students from cohorts 2 to 6 are presented in SI, Fig. A.1. We adopted the same classification here for data related to self-efficacy, and we adapted this classification to the total individual scores related to the reduction of anxiety based on the 20-items CLAI questionnaire with 5-point Likert type scale as follows: 20 to 39 points (low anxiety reduction), 40 to 59 points (below average anxiety reduction), 60 to 79 points (above average anxiety reduction), and 80 to 100 points (high anxiety reduction). Results for students from all cohorts are presented in SI, Fig. A.2.

Descriptive statistics and boxplots were obtained using the Excel software. Non-parametric statistical tests were applied, considering the initial ordinal character of our data and the limited number of students in the cohorts. The non-parametric statistical test of Kruskal–Wallis was performed for comparing several sets of data (unpaired data) for each dimension explored in order to investigate for a potential cohort effect. When considering all the data relative to a construct, the non-parametric statistical Friedman test was performed to assess if the consultation of the CHIMACTIV website impacts differently the dimensions of this construct (paired data). In case of rejection of the null hypothesis of the Friedman's test, a Conover's *post hoc* analysis was performed to investigate statistically significative differences between two dimensions.

Finally, to determine correlations between the dimensions of the two constructs, the Spearman Rho correlation coefficient was calculated. Statistical tests were performed using the corresponding Excel tools from the Anastats website (https://www.anastats.fr/telechargements/), with additional confirmation of test results on the BiostaTGV online platform (https://biostatgv.sentiweb.fr/?module=tests), except the Conover's *post hoc* test performed using the JASP software (version 0.95.4).

Results

Only students who consulted the CHIMACTIV resources were considered. They represent a major part of our target audience: 83.4 to 100.0% of the respondents depending on the cohort as indicated in Table 1. The questionnaire response rate was elevated for future scientists and engineers (cohorts 3–6, ranging from 80.0 to 94.0%) as shown also in Table 1. On the other hand, it remained around 43% for students from the teacher training college (cohorts 1–2); this observation was disappointing since we initially expected that future teachers might be enthusiasts for exploring digital resources and providing data to assess their pedagogical benefit for the students. Anyway, we have considered that these response rates were sufficient to use the data collected in our study.

Whatever the construct explored, anxiety or self-efficacy, the questions were all turned positively, so that responses indicating student agreement were in favour of the benefit of using the CHIMACTIV resources.

Usages of CHIMACTIV resources within our cohorts

When considering all cohorts, the majority (59.6%) of our students who declared using the CHIMACTIV website

Table 2 Details relative to the experimental part allocated in each program included in this survey, as well as to the schedule and organization of the experimental sessions (the durations indicated are those scheduled for students in their timetable)

Cohort code	Duration of the teaching unit and period covered	Content of the teaching unit	Total duration allocated to experimental work	Schedule of the sessions for the experimental work	Laboratory instruction style according to Domin (1999)	Laboratory instruction style according to Buck *et al.* (2008)	Expected production from students	Moment when students were asked to complete the questionnaire
1	5 h over 6 weeks	Theoretical lecture, experimental and feedback sessions	4 h	1 lab session of 4 h	Problem-based	Guided inquiry	Report	End of the teaching unit
2	7 months	Experimental sessions only	120 h	30 lab sessions of 4 h	Expository	Structured inquiry	Oral presentation	End of the academic year
3	40 h over 2 weeks	Experimental sessions only	40 h	5 lab sessions of 8 h	Expository	Structured inquiry	Report	End of the teaching unit
4 and 5	80 h over 4 weeks	Theoretical lectures, tutorials and experimental sessions	28 h	4 lab sessions of 7 h + 1 post-lab session of 3 h in autonomy (data treatment and interpretation)	Problem-based	Guided inquiry	Report	End of the teaching unit
6	48 h over 4 weeks	Theoretical lectures and experimental sessions	17 h	2 lab sessions of 4 h + 3 post-lab sessions of 3 h in autonomy (bibliography analysis, data treatment and interpretation)	Expository	Structured inquiry	Poster	End of the teaching unit

consulted these resources between 2 and 5 times as illustrated in Fig. 3a. It is important to point out that near 25% of them used these resources from 6 to 10 times during the considered course, and even 9% declared more 11 times of more. The average time per consultation was primarily (42.7% of our respondents) between 5 and 15 min during our study as shown in Fig. 3b. Again, extensive consultation of the CHIMACTIV website was noted for some students, with average time per consultation in the range 15 to 30 min for near 25% of our respondents, and even 10% of them who declare to spend 30 min or more (even above 1 h) on average for each consultation.

Students' perception of their experimental self-efficacy after consulting CHIMACTIV resources

For self-efficacy, the percentage of agreement ranged from 49.3 to 86.8% depending on the questions and considering cohorts 2 to 6 all together as illustrated by Fig. 4. Values were above 50% for all questions except one (Q5) but the percentage is near 50% for this question. The highest values are observed for the dimension "understanding concepts" (Q1–Q3, with values in the range 76.3 to 86.8%). The second dimension with elevated percentages is "sufficiency of resources" (Q10–Q12, with values ranging from 60.5 to 73.6%). This tendency is observed for each cohort separately, except in the case of cohort 5 with a value of only 47.4% for Q11. Interestingly, for cohort 6, the dimension "procedural complexity" (Q7–Q9) faces values for the percentage of agreement that are very similar to the dimension "sufficiency of resources" (53.3 to 86.7% to be compared to 66.7 to 86.7%); the same tendency is visible for cohort 2 (50.0 to 100% to be compared to 83.3 to 100%).

The benefit of consulting the CHIMACTIV resources on students' perception of their chemistry lab self-efficacy is observed.

The classification of students according to their total individual score reveals that most (92%) of our students perceive an increase in their self-efficacy thanks to the CHIMACTIV resources consultation (high self-efficacy for 37%, and above average self-efficacy for 55% as illustrated in SI, Fig. A.1). The remaining 8% of students present total scores corresponding to a below average self-efficacy.

Considering cohorts 2 to 6 together, mean score values ranged from 3.53 to 4.16 depending on the dimension of self-efficacy explored (see Fig. 5) (mean scores ranged from 3.42 to 4.24 for individual questions as indicated in SI, Table A.5). A Friedman test revealed that the score differences among the dimensions were significant (p-value < 0.001). Pairwise comparison with the Conover test indicated that the "understanding concepts" dimension had a mean score value (4.16) significantly higher than the scores of any other dimension (p-values < 0.001). Also, the "sufficiency of resources" dimension faced a mean score (3.85) higher than the one reported for the "procedural complexity" and "laboratory hazards" dimensions (p-value 0.008 and 0.006, respectively). For each of the self-efficacy dimensions considered, the Kruskal–Wallis test revealed no significant effect of the cohort (p-values in the range of 0.094-0.917).

Table 3 Values of the Cronbach's alpha

Dimension explored	Cohort 1	Cohort 2	Cohort 3	Cohort 4	Cohort 5	Cohort 6	All cohorts	Cohorts 2–6
Chemistry laboratory anxiety								
Working with chemicals	0.87	0.96	0.91	0.89	0.86	0.90	0.90	
Using equipment and procedures	0.82	0.88	0.90	0.88	0.72	0.87	0.85	
Collecting data	0.82	0.98	0.94	0.77	0.80	0.87	0.87	
Working with other students	0.97	0.97	0.93	0.96	0.96	0.88	0.94	
Having adequate time	0.93	0.95	0.96	0.87	0.83	0.94	0.91	
Experimental self-efficacy								
Conceptual understanding	0.55	0.83	0.85	0.94	0.92	0.75	0.85	0.87
Laboratory hazards	0.68	0.83	0.89	0.94	0.52	0.86	0.83	0.84
Procedural complexity	0.32*	0.97	0.86	0.74	0.88	0.67	0.82	0.84
Sufficiency of resources	0.57	0.65	0.79	0.87	0.88	0.73	0.78	0.80

values above 0.60 are considered acceptable, values in the range 0.50–0.60 are low but still acceptable, * values below 0.50 are considered unacceptable.

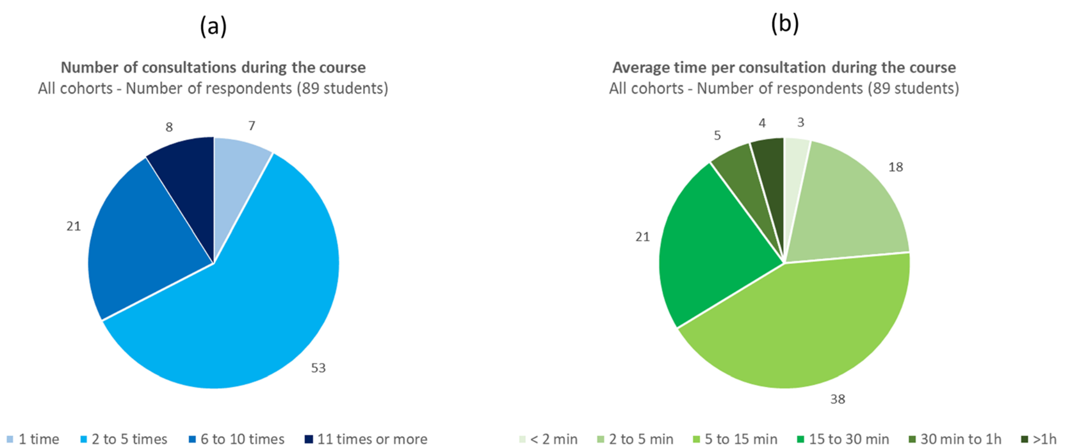

Fig. 3 Usages of the CHIMACTIV website, considering all cohorts (89 students): (a) number of consultations by the students during the considered course; (b) average time per consultation.

Students' perception of their chemistry laboratory anxiety after consulting CHIMACTIV resources

The percentage of agreement with the questions relative to anxiety ranged from 32.6 to 65.4% depending on the questions and considering all cohorts together (see Fig. 6). Values were above 50.0% for five questions: Q2, Q3, Q7, Q12 and Q17. It is interesting to notice that four of them explore the same dimension that is "using equipment and procedures". Looking in detail of data by cohort, another interesting result can be noticed. For future teachers' students (cohorts 1 and 2), values were also above 50.0% for the four questions relative to "collecting data" (Q3, Q8, Q13 and Q18); for cohort 6, the same tendency was observed for the anxiety dimension "working with other students" (Q4, Q9, Q14 and Q19). Since our questions were formulated with positive assertions, this clearly indicates the positive impact of consulting the CHIMACTIV resources on students' chemistry lab anxiety.

The classification of students according to their total individual score reveals that a large majority (78%) of our students perceive a reduction of their anxiety thanks to the CHIMACTIV resources consultation (high anxiety reduction for 24%, and above average anxiety reduction for 54% as illustrated in SI, Fig. A.2). Only 2% of our students present a total score corresponding to a low anxiety reduction.

Considering all cohorts, mean score values ranged from 3.24 to 3.71 depending on the dimension of anxiety explored as shown in Fig. 7 (mean scores ranged from 3.12 to 3.85 for individual questions as indicated in SI, Table A6). The Friedman test revealed that score differences among the dimensions were significant (p-value < 0.001). Pairwise comparison with the Conover test showed that the mean score value (3.71) observed for the "using equipment and procedures" dimension was significantly higher than the scores obtained for any other dimension (p-values in the range < 0.001 to 0.031). The score attributed to the "collecting data" dimension was lower (3.54), but still significantly higher than the scores of the dimensions "working with chemicals", "working with other students" and "having adequate time" (Conover, p-values in the range < 0.001 to 0.009 depending on the other dimension considered). For each of the anxiety dimensions considered, the Kruskal–Wallis test revealed no cohort effect (p-values in the range 0.135–0.844), so that mean scores were similar among our cohorts.

Correlation between experimental self-efficacy and chemistry laboratory anxiety

A positive and significative correlation was observed between the reduction of anxiety and the increase of self-efficacy as

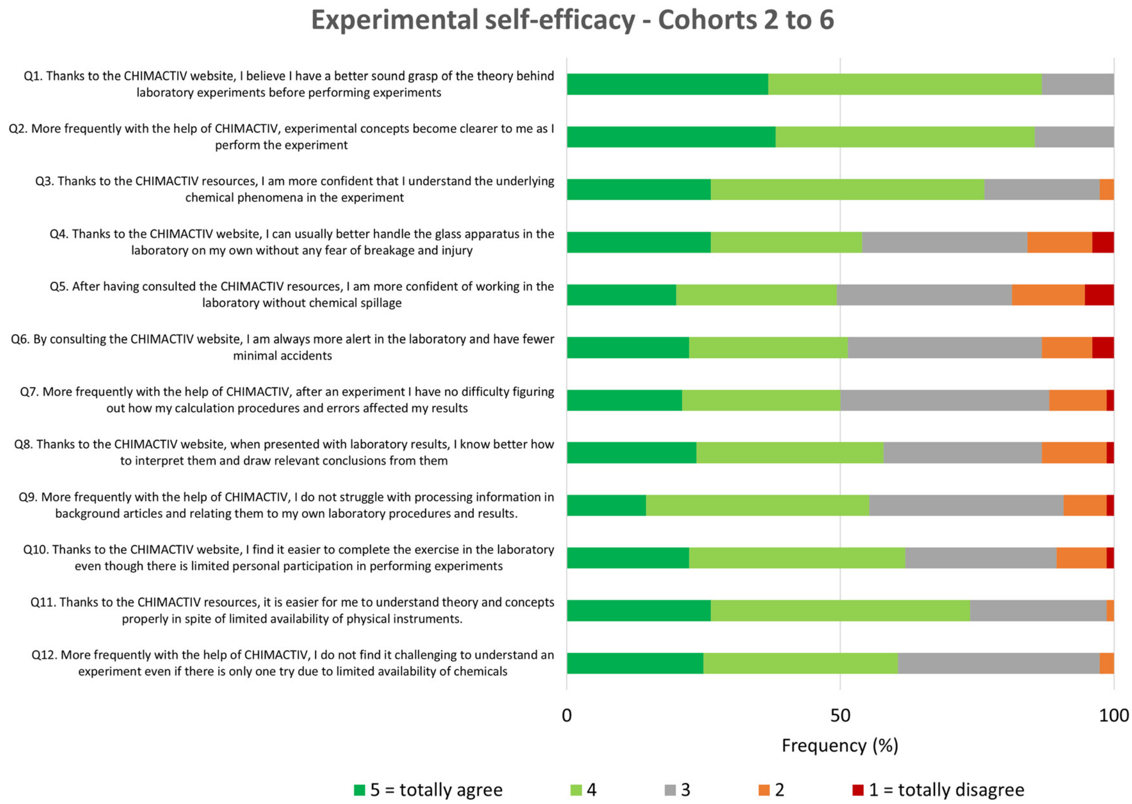

Fig. 4 Percentage of agreement for all questions relative to experimental self-efficacy, considering cohorts 2 to 6 (76 students).

indicated by the correlation coefficients shown in SI, Table A7. Values for these coefficients ranged from 0.40 to 0.67 (p-values in the range 2.3×10^{-11}–0.0004). Overall, 55% of the coefficients are above the value of 0.50, indicating a strong correlation between the dimensions concerned. The highest value was observed between the two dimensions "using equipment and procedures" (anxiety) and "sufficiency of resources" (self-efficacy), followed by a similar value (0.65) between the two dimensions "working with chemicals" (anxiety) and "laboratory hazards" (self-efficacy). Interestingly, all the five dimensions of anxiety are strongly correlated to the dimension "sufficiency of resources" of self-efficacy (values above 0.51). Also, the dimension "laboratory hazards" (self-efficacy) was strongly correlated to three dimensions of anxiety, namely "working with chemicals", "working with other students" and "using equipment and procedures" (values above 0.52). Two other strong correlations were observed: between "conceptual understanding" (self-efficacy) and "using equipment and procedures" (anxiety), as well as between "procedural complexity" (self-efficacy) and "working with other students" (anxiety) (values above 0.53). Several subscale correlations are graphically presented in Fig. A3 of the SI.

Discussion

Usages of the CHIMACTIV website before lab sessions

One major result of our study is the elevated rate of using CHIMACTIV resources among our respondents. From our experience, this may be strongly related to the teacher attitude to invite students to consult specific resources, and also partly dependent on the reuse of the knowledge explored on the website in class or in lab sessions. In case of cohort 3, students were strongly invited by the teacher to answer an online quiz (available on the learning management system of the university) before the lab session, where answers may be found in the CHIMACTIV website; students had no obligation to access the CHIMACTIV website to answer the quiz, but it was highly recommended by the teacher who provided the direct link to facilitate access to the topic related to the quiz. Students who did not complete this activity were reminded by the lecturer before the practical sessions to encourage them to carry out this preparatory work. This teaching strategy resulted in 100% of the students who have consulted the website.

By combining the preferred number of consultations (2 to 5 times for 59.6% of our students) with the preferred time per consultation (5 to 15 min for 42.7% of our students) reported by our students, the more frequent preparation time with the CHIMACTIV website in this study was in the range 10 to 75 min, that is quite similar to the time reported in a previous study where students had to complete prelab e-quizzes and were encouraged to view instructional videos before analytical chemistry practical classes (*i.e.* time ranged mostly within 15 and 60 min or more, with 29.2% of students reporting to spend 60 min or more) (Jolley *et al.*, 2016). Looking in detail into the data, it appears that only students from cohorts 3 and 6 reported a consultation time above 60 min (this concerns a

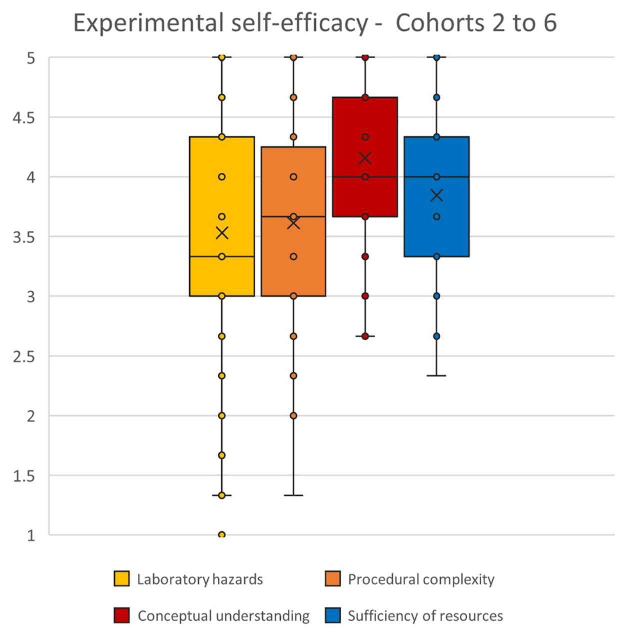

Fig. 5 Boxplots of the scores obtained for the four dimensions of experimental self-efficacy considering cohorts 2 to 6 (76 students)

total of four students, two from each cohort). This is in line with the online quiz completion required for entering the lab session for cohort 3, that encourages the students to consult the CHIMACTIV website to find the correct answers.

Benefits of the CHIMACTIV website consultation on students' experimental self-efficacy

Mean score values per dimension as well as individual total score values related to self-efficacy are rather high in our study. By comparison, a mean score value of 3.4 has been recently reported for chemical laboratory self-efficacy using a scale composed of 15 items in a 5-point Likert type (Sailaubay *et al.*, 2024). Also, even if we cannot directly compare our results with those reported by Kolil *et al.* (2020) since they performed pre- and post-tests, our scores exceeding the average self-efficacy are higher than the values they reported for their pre-test.

Thus, our results are clearly in favour of a benefit on students' chemistry laboratory self-efficacy belief of consulting the CHIMACTIV resources to prepare the lab sessions. The greatest benefit relates to the "understanding concepts" dimension; this could be explained by the theoretical content provided by the CHIMACTIV website, which enables students to better get the meaning of concepts. This is in line with previous results of Saleh (2009) reporting that students who consulted visualization resources related to experiments before chemical lab sessions improved their understanding of concepts and experimental procedures as compared to students who did not.

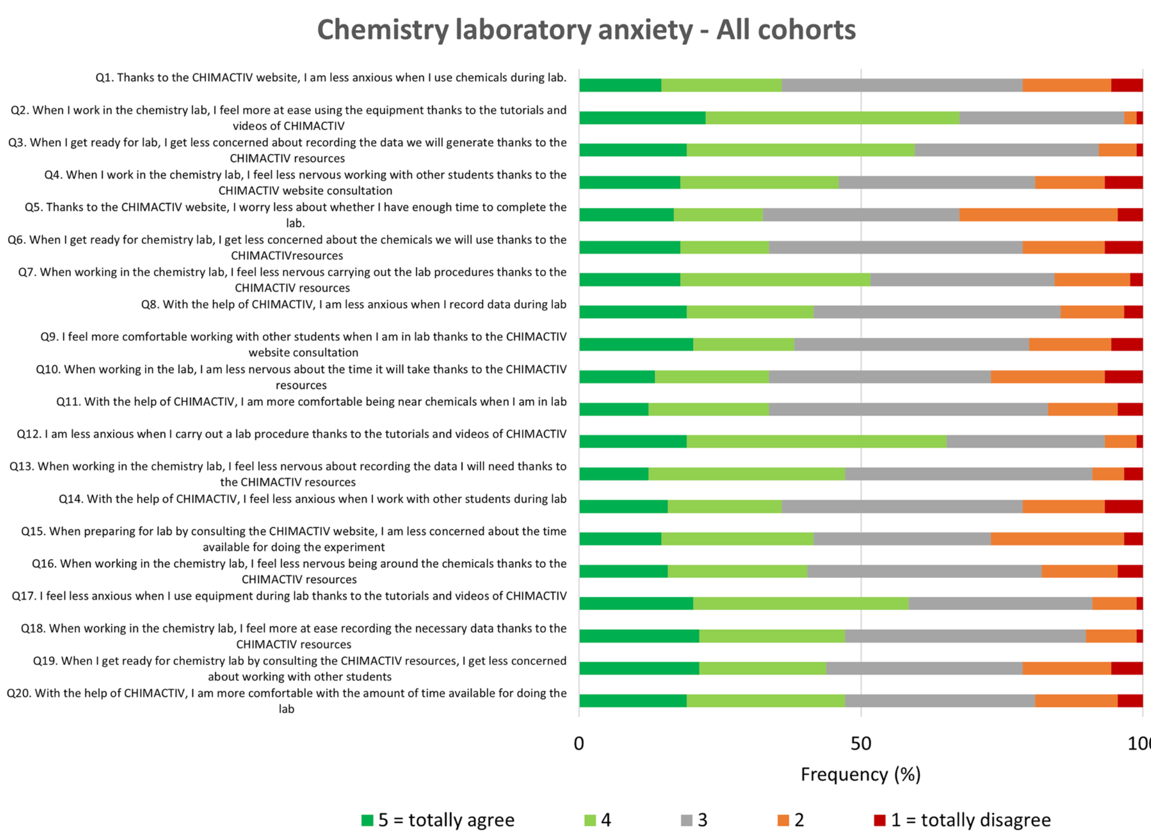

Fig. 6 Percentage of agreement for all questions relative to chemistry laboratory anxiety, considering all cohorts (89 students).

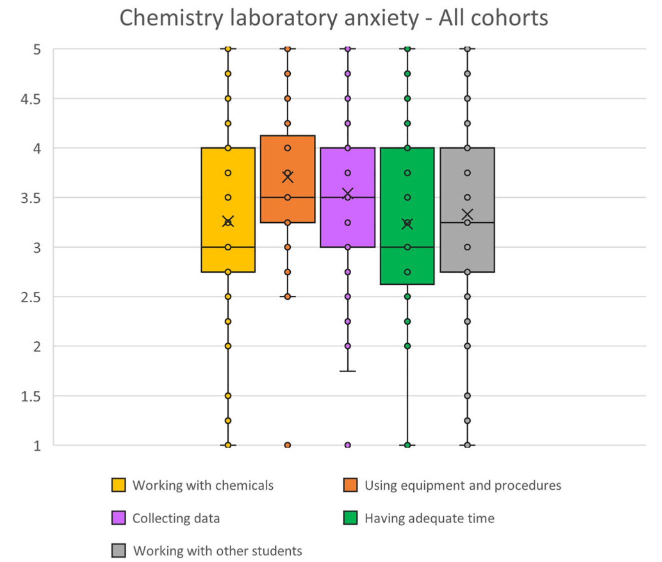

Fig. 7 Boxplots of the scores obtained for the five dimensions of chemistry laboratory anxiety considering all cohorts (89 students).

Benefits of the CHIMACTIV website consultation on students' chemistry laboratory anxiety

With regard to chemistry laboratory anxiety reduction, the positive effect of consulting the CHIMACTIV resources was observed whatever the dimensions considered (mean score values above 3.20). It was the most pronounced for the dimension "using equipment and procedures" (mean score 3.71, standard deviation 0.76). This result was predictable, as several of the resources to which students were directed contain experimental details and short videos describing how to use laboratory equipment.

A significant positive effect was also observed for the dimension "collecting data" (mean score 3.54, standard deviation 0.81). We formulate the hypothesis that since students feel more prepared for the lab sessions due to a better understanding of the procedures and how to use the equipment thanks to their consultation of the CHIMACTIV website, there are less anxious for collecting the data during the lab sessions. In addition, due to the responsive digital character of the CHIMACTIV resources, their consultation during the lab sessions is possible, and this could also lead to a reduction of students' anxiety. Indeed, Damo *et al.* (2020) gave evidence (using the LAQ questionnaire with pre- and post-test) that the integration of mobile applications and videos during lab sessions significantly decreased students' chemistry lab anxiety.

It is noteworthy that our results were similar whatever the cohorts, so that the students' perceptions were comparable for chemists, biochemists and biologists. This was unexpected as previously mentioned. Hence, as we hypothesised that biologists (and possibly biochemists) may have more negative attitudes towards analytical chemistry than chemists, with subsequent higher chemistry anxiety for biologists (and possibly biochemists) than chemists since negative chemistry attitudes were reported to create chemistry anxiety (Kurbanoglu and Akim, 2012), we expected biologists (and possibly biochemists) to face a higher chemistry laboratory anxiety than chemists. Nevertheless, since we measured students' perception of anxiety reduction, possibly they experienced the same perception but we cannot exclude the fact that, on the whole, biologists (and possibly biochemists) faced a higher chemistry laboratory anxiety than chemists. At least this clearly suggests the broad scope of applications of the CHIMACTIV resources in chemistry laboratory teaching programmes.

Correlation between experimental self-efficacy and chemistry laboratory anxiety

The correlation coefficients assessed in our study between dimensions of chemistry laboratory anxiety and experimental self-efficacy are in the same range than those previously reported by Rummer *et al.* (2019). In our case, values are all positive since we formulated all the questions relative to anxiety as a positive effect of the CHIMACTIV resources, so that we measured a reduction of perceived anxiety instead of assessing the perceived anxiety. Our results do confirm that an increase in experimental self-efficacy is related to a decrease in chemistry laboratory anxiety.

Significant correlations were observed across all dimensions, with 55% of correlations exceeding 0.50, indicating consistently strong relationships between specific aspects of anxiety and corresponding self-efficacy dimensions. These patterns broadly align with Kolil *et al.* (2020), who reported that all dimensions of self-efficacy contribute to student anxiety in laboratory tasks. Interestingly, the strongest link in our study involved "using equipment and procedures" (anxiety) and "sufficiency of resources" (self-efficacy), providing additional insight compared to Kolil *et al.* who identified "conceptual understanding" as the most impactful dimension. Notably, all five dimensions of anxiety were strongly correlated with the "sufficiency of resources" dimension of self-efficacy (values above 0.51), which was the least impactful in Kolil's study. This difference may reflect the context of our study, which involved near a hundred of undergraduate students *versus* Kolil's much larger cohort (over 1000 participants).

Implications

It is now well-established that academic self-efficacy is a good predictor of academic achievement and performance (Artino, Jr, 2012). We may hypothesise that this is similar in the context of a chemical laboratory. During experimental sessions, students' self-efficacy belief will influence their motivation, engagement and performance in the tasks. Indeed, recent results showed a positive and significant relationship between the academic achievement of students in a chemical technology course and their laboratory self-efficacy (Salaubay *et al.*, 2024).

Our results suggest that teachers may consider integrating digital pre-laboratory resources (such as CHIMACTIV in the field of analytical chemistry) into course design, particularly for students with limited prior experience in chemistry.

These resources may help structure students' preparation before laboratory sessions, especially in contexts where anxiety and low self-efficacy are common among less experienced learners. Given that first-year university students are often reported to experience high levels of chemistry anxiety (chemophobia) due to limited prior experience (Eddy, 2000), such resources may be particularly relevant at the beginning of university curricula. Teachers can guide students toward specific CHIMACTIV modules depending on pedagogical objectives, such as reinforcing prior knowledge, introducing new scientific concepts, or supporting data analysis skills. The interactive and adaptive nature of these resources makes them suitable for both practical and theoretical learning contexts. In addition, their possible consultation on any digital support favors their use during the experimental sessions, so that students may complement their pre-laboratory work during these sessions.

Limitations

While the overall number of participants was adequate, some cohorts included relatively few students, and participation rates varied across groups. These factors may limit the generalizability of the findings and suggest that results should be interpreted with caution. In addition, data were collected by the teachers themselves, at the end of the considered courses, who were also the designers and creators of the CHIMACTIV resources. Consequently, our data may be affected by a desirability bias, although the responses to the questionnaire remained anonymous. Our results should be confirmed on larger cohorts, and possibly in other educational contexts, especially by considering first-year and second-year undergraduate students since they were absent from our cohorts.

Considering our instrument, we used a Likert type scale presented as a numerical rating scale, with 1 indicating ''totally disagree'' and 5 indicating ''totally agree''. For the ESE questionnaire as well as the CLAI questionnaire, Kolil *et al.* (2023) and Bowen (1999), respectively, preferred to use the indications of ''strongly'' instead of ''totally''. We are aware of the fact that this minor difference may have influenced the students' answers, and possibly this may explain the elevated percentage of neutral (value of 3) answers in our data (mean value of 38% for anxiety with a range covering 20 to 60%; values are lower for self-efficacy, with a mean value of 28% and a range covering 13 to 38%). In addition, we cannot exclude the fact that some students chose the neutral option since they believed their true response was not desirable.

In addition, the two revised questionnaires we used in this study should have been tested, especially since the initial versions were validated in the English version when we used a translated French version, and also since we made changes to the initial wording of the questions. It would have been more rigorous to validate that they are still aligned with the anxiety and self-efficacy models considered, by performing a confirmatory factorial analysis.

Also, our instrument provided data on anxiety related to the chemistry laboratory, without distinguishing between the different types of anxiety. It would be particularly interesting to gather further information in order to distinguish between ''achievement anxiety'' (related to performance, success or failure) and ''epistemic anxiety'' (related to knowledge and the generation of knowledge); this would help teachers to better support their students by helping them to manage and alleviate their anxiety. These two types of anxiety have recently been clarified in the context of the analytical chemistry laboratory: ''achievement anxiety'' (or ''performance anxiety'') is experienced ''when students are afraid of not being able to operate certain instruments, making procedural mistakes, and not being able to finish on time'', whereas ''epistemic anxiety'' arises ''when students experience the discomfort of not knowing why something went wrong in the experiment'' (Agustian *et al.*, 2025 , p. 732). The ''Epistemically Related Emotion Scales'' instrument could be used (Pekrun *et al.*, 2017), especially in its short version, to track the dynamics of ''epistemic anxiety'' (as well as other epistemic emotions) among students in the chemistry laboratory.

Finally, we have regarded anxiety here as a negative emotion that hinders learning. Previous findings have shown that its role is more ambiguous. ''Achievement anxiety'' can sometimes be beneficial for learning (for example by inducing motivation to work harder) (Pekrun and Stephens, 2012). On the other hand, ''epistemic anxiety'' may play a role in guiding cognitive processes and driving scientific inquiry (Agustian *et al.*, 2025).

Conclusions

Our results show that when learners consult targeted resources (selected by the teacher) on the CHIMACTIV website before the experimental sessions, they perceive an increase in their self-efficacy and a reduction in their anxiety in the chemistry laboratory. This is aligned with the observations made by our teachers during the sessions, who note that students who have visited the site behave in a more proactive and thoughtful manner than students from previous cohorts who did not have access to these digital educational resources.

All of this suggests that consulting the CHIMACTIV site has a beneficial effect on chemistry learning. The originality of our study lies in the fact that we have considered different higher education contexts (teacher training college, university, and an engineering school), covering several academic levels, students' profiles, as well as laboratory instruction styles. Our results also confirm the strong correlation between experimental self-efficacy and chemistry laboratory anxiety.

These findings and the observed correlations would benefit from replication in other contexts or with larger sample sizes, particularly given the differences observed compared to Kolil *et al.* (2020). A mixed-methods study incorporating interviews could also provide a deeper understanding of the mechanisms underlying these effects.

Author contributions

All authors contributed to data collection, writing – review and editing, as well as funding acquisition. Valérie Camel's additional contribution was conceptualization, data curation, formal analysis methodology, validation, visualization, writing – original draft. Jonathan Piard's additional contribution was conceptualization, data curation and formal analysis methodology.

Conflicts of interest

There are no conflicts to declare. The authors will have no financial nor professional benefit related to the external use of the CHIMACTIV website. The same applies to the institutions to which they belong.

Data availability

The data supporting this article have been included as part of the Supplementary Information (SI). In addition, raw data may be deposited on an open access repository if this is of interest to the teaching or scientific community. Supplementary information is available: Tables A1–A7 and Fig. A1–A3 are given in the SI. See DOI: https://doi.org/10.1039/d6rp00091f.

Ethical considerations

Informed consents were obtained from the students to participate in this study, and filling the questionnaire was optional for them. As this step occurred at the end of the teaching unit, this did not influence the consultation of the CHIMACTIV resources before the laboratory sessions nor the behaviour of students during these sessions.

The researchers were also the teachers, but they did not deliver any extra mark for filling the questionnaire and participating in the study, and students who did not respond were not penalized. As a matter of fact, since all the collected responses were anonymous using an online questionnaire, the researchers had no information about the persons responding. Students' profile data were collected to give an indication about previous scientific knowledge of the respondents, but at the end these data remained untreated. Hence, individuals' privacy and confidentiality have been protected.

The study was conducted in line with the ethical guidelines of the three institutions concerned (AgroParisTech, ENS Paris-Saclay and UFR Sciences from the Université Paris-Saclay).

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