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Learner agency in a chemical engineering curriculum: Perceptions and critical thinking

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ABSTRACT

The extent to which learners have scope and opportunity to direct and influence their own approach to learning activities, what may be termed 'learner agency', has been shown to be important for students across many disciplines, in developing key advanced skills and qualities such as self-efficacy, critical thinking, resilience and innovative problem-solving. Employers unsurprisingly value graduates able to exhibit and cope with agency in their approach to work through such elements as self-learning ability, capacity to formulate and solve open-ended problems, coping with unfamiliar situations, and effective teamwork. Here, through a student-led and student-designed research project using questionnaire and interview methodology, we explore *via* the perceptions of students themselves how a typical UK Chemical Engineering BEng/MEng curriculum provides opportunities for agency and how students feel they cope with agency. We examine the curriculum class-by-class and year-by-year, studying correlations and patterns in the types of learning activity which students perceive as enabling them to exert influence and control over learning. In follow-up one-to-one interviews we further examine the link between perceived degree of agency and critical thinking skills, as measured by standardized scales, to explore how perceived agency-delivering activities may correlate with actual developments in thinking styles and skills.

1. Introduction

In this paper we focus on the concept of learner agency, and explore to what degree a typical UK Chemical Engineering BEng/MEng curriculum is perceived by its students as offering opportunities for those students to exert their own agency over their learning. We also explore the link between students' perception of the agency offered by particular classes and the degree to which those classes enhance their critical thinking skills. While the research is focussed on a single discipline (Chemical Engineering) in a single mode of study (full time) at a single University (the University of Strathclyde, Glasgow, UK) the issue of how students are prepared by their higher education to cope with and benefit from agency is core to all graduate experience and its impact on societies. As our next generations of graduates contribute to a more sustainable, more equitable society, help mitigate the effects of climate change, and enhance the wellbeing of human populations and the environment globally, undoubtedly they will be called on to make difficult decisions and judgements, approach unfamiliar problems with confidence and a critical view, and be ready to innovate in sustainable, equitable ways. The question of how higher education prepares graduates for these challenges, that go beyond topic-specific and technical knowledge and skills, is urgent and vital.

The paper is organised as follows. First we give a brief overview of the underlying issues of agency in education, put into context of the current literature and connecting to the concept of critical thinking. Then we describe our research methodology, present and discuss our results, and finally draw some conclusions.

1.1. Agency and learning

The topic of agency is vast and sprawls across many disciplines. The concept of agency has roots in the deepest psychological and social foundations of human existence (Kockelman, 2007; Emirbayer and Mische, 1998; Cote and Levine, 2002) and continues to ignite fierce discussion across disciplines from philosophy and social science to neuroscience, in the public as well as academic sphere (Burkeman, 2021). Researchers have associated agency with a wide set of concepts, from *intentionality* to *choice* to *self-efficacy* (Ramsey, 2017; Nieminen and

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Tuohilampi, 2020; Charteris and Smardon, 2018). Broadly agency can be defined as 'the power to create change' (Goller and Paloniemi, 2017). While our interest here is specifically on agency in education, Biesta and Tedder (2007), in their suggestion to 'see agency as the ability to exert control over and give direction to one's life' demonstrate that the question of agency is relevant to the whole of the lifecourse, linking the way education prepares individuals to cope with and benefit from agency to major questions of lifelong learning. From an employability perspective, it is almost stating the obvious to remark that employers are likely to value graduates who can act successfully with agency—making their own reasoned decisions, solving open-ended and unfamiliar problems, showing perseverance and resilience, working with others and across unfamiliar contexts, and so on. Numerous surveys demonstrate this unequivocally in the chemical engineering sector (World Chemical Engineering Council, 2004, Fletcher et al. 2017).

When it comes to agency specifically in education, there are (at least) two aspects to the issue: how education helps an individual develop their own capacity to cope with situations where they have agency, with resulting benefits in life and work; and to what degree and in what ways learners have agency or influence over and during their actual educational experience. Considering the first of these aspects, it seems reasonable to suppose that a newborn infant has very little agency: as a part of growth, a person therefore must *learn* to act with increasing agency, and formal education presumably has a significant role to play in this, although exactly what role is not necessarily clear (Hunter, 2020). The second aspect, the issue of students having agency or control over their learning experience itself, has been much discussed in educational literature spanning at least a century from Dewey (1922), who posited agency as a counter to behaviourism, through to Bandura (2001), whose work emphasises the link between an individual's agency and their sense of self-efficacy.

The wider literature around agency quickly reveals a fundamental tension, associated with where agency is *located* (Cote and Levine, 2002). Is agency a quality of the individual, arising from psychology? Or is agency provided to an individual by their environment through essentially sociological mechanisms? Various authors explore how agency and the student's response to agency opportunity are not necessarily entirely determined by the individual's disposition (Tsai et al., 2020; Case, 2015; Nieminen and Tuohilampi, 2020; Crick and Goldspink, 2014). Amongst direct examinations of the impact of context and environment, Czerniewicz et al. (2009) studied the roles of social constraints on agency amongst students and the connection with the social equity agenda; while Charteris and Smardon (2018) considered the role of educational environment, including materials and spaces, in providing and supporting student agency. In fact as Cote and Levine (2002) imply, the answer to the psychological *vs* sociological origin debate for agency is likely to be 'a bit of both'. There is an inevitable crosstalk between the portfolio of learning activities and learning environment presented to the student (the sociology), and how their innate psychology influences their response to this environment. For example we may try to take the 'environment' perspective, and imagine that agency opportunities intrinsic to the course curriculum are 'delivered' to students through designed learning activities. Yet it cannot be assumed that students will respond in desired or expected ways: their psychology will also have a role to play. Indeed we may observe this directly in the context of chemical engineering students: Sharif (2022), studying student experience in the capstone Design Project, shows that students provided with open-ended problems featuring clear opportunities for agency, actually often follow a 'constraint creation' strategy, deliberately attempting to 'close the task down', seemingly to reduce the anxiety and uncertainty involved in making one's own decisions and judgements. Hence it is not enough to take the sociology perspective and design a curriculum brimming with agentic learning activities: we also need to understand how different aspects of an activity, its context, and the students' own dispositions, either encourage or discourage students from responding in ways that make use of the agency opportunity provided and that improve, through engaging with the agentic experience, their capacity to act with agency.

Moreover there are connected policy and pedagogy dimensions to the underlying tension of agency in education. Consider the following schematic example: compare a course or module that has been designed with precise, pre-defined learning objectives and fully specified assessment criteria, to a group project with open-ended, perhaps even student-driven or co-created aims and assessments. The former might seem to give very little opportunity or motivation for students to take different routes toward learning. The latter more open-ended activity meanwhile seems to guarantee at least the opportunity of student-driven choice and decision (notwithstanding the above comments about whether students choose to engage with agency or try to avoid it): yet its potentially ill-defined learning objectives might at the very least raise some eyebrows at accreditation and quality-assurance panels. There is then a policy tension: the fundamental learning objective- and knowledge-inquiry driven approach of modern universities may seem to work against enhancing agency-related skills, and indeed has come in for criticism as effectively putting limits on learning, taking away student agency (Lawton, 1984; Maxwell, 2021; Hunter, 2020). And yet any teacher will be well aware of the demand amongst students and quality-assurance bodies, in many ways perfectly understandable, for crystal-clear objectives, assessment criteria and performance expectations, linked also to the 'professionalisation' agenda in school and higher education (Koster and Dengerink, 2008).

Turning to pedagogy, Sfard's (1998) discussion of learning as either 'acquisition' or 'participation' may be applied to our comparison of lecture-based class and open-ended project. From the point of view of agency one might, simplistically, characterise acquisitive learning from lectures as low agency, students simply 'absorbing' the material put in front of them, compared to a highly agentic 'participation' in a learning community undertaking a project (Lave and Wenger, 1991). But reality is perhaps not quite so black and white. There is potential for choice in acquisition: where to focus one's efforts, how to assemble useful understanding or problem-solving skill from a smorgasbord of facts, how to judge the point at which what has been acquired is 'enough'. Conversely there may be lack of agency in participation: behaviour may be driven by peer pressure, particularly amongst status-conscious children/young adults; or indeed conditioned by culture, background and perceived 'identity' (Nisbet et al., 2016; Hunter, 2020).

What this discussion illustrates is that issues of agency are not likely to be clear cut even in scenarios that might seem obvious at first sight. Agency is thus such a broad and complex issue that further clarification or breakdown into components would seem useful. In this vein Vaughn (2020) introduced a 'multidimensional' model of learner agency, involving what she calls 'disposition' (agentic action driven by the basic intentions and drives of the student), 'motivation' (agentic action driven by the goals in some sense externally imposed, such as achieving grades, overcoming topic-specific or even class-specific challenges) and 'positional' (agentic action driven by the social context, such as relating to or working with other students). This model acknowledges some of the tensions of agency discussed above: disposition is perhaps dominated by the individual's psychology, while motivation admits the impact of the external context, and position adds a social, human context which itself combines psychology and human environment. Therefore while Vaughn (2020) ultimately seems to plump for the sociology side of the debate, stating that 'agency is socially constructed', the model itself does more to embrace the duality of individual/environment.

The role of agency specifically in engineering education has been studied extensively for example by Felder and colleagues (Felder and Silverman, 1988; Prince and Felder, 2006; Felder and Brent, 2004; Felder, 2012). A wider literature explores more generally how student agency relates to the development of 'identity' amongst learners (Cote, Levine, 2002; Holland and Lachicotte, 2001; Biesta et al., 2008; Sfard and Prusak, 2005), in which vein Litzinger et al. (2011) discuss the development of engineering 'expertise', a concept linked to 'professional

identity' and, bringing us back to policy, currently dominant economic and employability drivers in HE (Wolf, 2002; Belfield et al., 2018; Winberg et al., 2020). On a more fundamental current driver in engineering, arguably more important than the earning power of engineers is the topic of sustainability: Svanstrom (2016) considers how the agency for change in sustainable practices can develop in chemical engineering students, while Wiek et al. (2011) take a wider view of competencies, many agency-related, required of graduates whose careers will focus on sustainability over the next decades.

The above literature makes a convincing case for the importance of exploring the role of agency in learning, considering both how learners respond to educational scenarios which invite exercise of agency, and the way a learning experience may develop students' capability to act with agency. These are broad and deep questions: to begin to address them here we examine a specific context, an undergraduate degree course in Chemical Engineering at a UK University. Ultimately one cannot really separate the *experience* of learning (which must be an experience particular to each individual student, since it consists of changes in knowledge, understanding, behaviour and skills correlating to physical changes in each individual's brain and body) from objective 'artefacts' of learning such as curriculum components, activities and so on. Nor is it easy to separate the student's psychology-driven response from their environmental 'history' (Crick and Goldspink, 2014). These inevitable overlaps are simply alternative expressions of the same psychology/sociology, individual/environment debate. In this project therefore, instead of 'taking sides' as it were, we take the psychology/-sociology, individual/environment debate not as a choice we need to make but as an inevitable duality: we explore how agency may be delivered by different aspects of a curriculum (environment) through the student's own perspective (individual). One might argue that such perception remains a step away from some kind of 'objective reality' of which learning activities provide agency and which don't: but that presupposes that the answer to the above individual/environment debate is emphatically 'environment', which as we have discussed is far from clear. One thing that does seem clear is that if a student does not *perceive* agency opportunities in a given activity, they are unlikely to act with agency. Hence from a practical point of view the perception that students have of the agentic opportunities offered by their course and how they have engaged with them are key factors in their gaining any benefit. It is worth mentioning that other approaches including development of validated scales of measuring student agency have been followed (for example Jaaskela et al. 2017) but again, in this work we simply directly explore students' perception of their opportunity to exercise agency: we aim for the student's eye view, in all its subjectivity and diversity.

1.2. Critical thinking

'Critical thinking', whatever its precise definition (Facione et al. 2000), is likely to apply to all areas of professional engineering (and indeed to most if not all other graduate disciplines). Recent decades have seen an increasingly explicit focus on critical thinking skills development in engineering education (Gunnink and Bernhardt, 2002; Adair and Jaeger, 2016; IChemE, 2020) while industry often cites greater critical thinking skills as a priority graduate attribute. The implied driver of these calls for enhanced skills is that greater inclusion of critical thinking in engineering classrooms would presumably see graduates more able to apply technical knowledge to problem scenarios, work more effectively in teams, use improved leadership skills and better address problems faced in engineering globally.

The question we explore here is whether there is a link between providing students with agency within their learning activities, and the development or improvement of critical thinking skills; and if so how this link manifests and could be strengthened. Although such a connection may seem intuitively reasonable (critical thinking aspects such as 'reflection', 'perseverance', 'goal motivation', seem likely to demand a student's own agentic action) the nature and depth of connections is not *a priori* obvious. The issue has been explored in the literature across a range of disciplines, which motivates us to begin to explore it in chemical engineering: Hand et al. (2018) showed that students participating in an immersive teaching approach within a science classroom, which increased their agency, had a higher growth rate on the Cornell Critical Thinking Test than students in traditional deductive classrooms. In ethnography, allowing students 'complete free will' enabled development of more agency and, in turn, the ability to think critically intensified drastically (Arias, 2008). In physics labs, undergraduate students were found to be more critical in assessing unexpected findings and providing data-backed conclusions, when they perceived a greater level of agency (Holmes et al. 2020). Our goal is not to develop any deep theoretical model for the linkage, which would require a substantially more developed experimental design, but at this stage to explore whether there are potential links between the relatively well-established educational 'lens' of critical thinking and the perhaps more diffuse concepts of agency. Such exploratory research may then aid the development of more detailed predictive models that would enable enhanced curriculum design to promote both critical thinking and agency skills.

One of the challenges of studying the provision of critical thinking skills is how to measure students' critical thinking development (Beyer, 1984; Fisher and Scriven, 1997; Bissell and Lemons, 2006). Methods such as the Cornell Critical Thinking Test, a widely used assessment within education, may not 'locate' results to specific modules or activities, and can take a substantial amount of time for both researcher and student. Alternative scales, such as the California Critical Thinking Dispositions Inventory (CCTDI; Facione and Facione, 1992), the Critical Thinking Disposition Scale (CTDS; Sosu, 2013) and the non-proprietary Student-Educator Negotiated Critical Thinking Dispositions Scale (SENCTDS; Quinn et al. 2020) measure critical thinking *disposition,* that is the inclination, tendency, or willingness to engage in specific critical skills/activities (such as reflection, open-mindedness etc). The scale explores a number of categories of students' dispositions including reflection, attentiveness, open-mindedness, organisation, perseverance, and intrinsic goal motivation. Because we are also particularly interested in students' capabilities in agentic self-guidance, we add a further element, 'knowledge and independent thinking'. Note that we do not here make detailed comparison with other direct implementations of SENCTDS, we use SENCTDS only as a starting point for developing a useful set of questions to explore critical thinking disposition and its potential correlation with agency perception. Further details on how these dispositions are measured are given below.

1.3. Research questions and aims

Our aim at this stage of the research is not to arrive at underlying general theoretical 'laws' of agentic teaching and learning (even assuming there are such things), but rather to explore the usefulness of agency as a way of examining the student experience, particularly in the context of UK chemical engineering education. This exploratory examination may then provide a basis for models and curriculum design tools/models to further promote student agency. We distil our aim into two broad research questions:

1. Where do students perceive there to be opportunities for agency within the Strathclyde full-time BEng/MEng Chemical Engineering UG curriculum and how do they engage with these?
2. What correlations are there between students' perceptions of the level of agency a given class offers, and their perceived development of a range of critical thinking skills?

Table 1
The Chemical Engineering BEng/MEng curriculum at the University of Strathclyde at the time of the reported study, including codes for modules. The study itself explored only years 2, 3 and 4 of the programme (codes listed in the right-most column) which are identical for BEng Hons and MEng, but the Table shows all years 1–5 for completeness. Year 5 is the MEng-only year in which students are offered a range of optional modules which tends to change from year to year. Note that some single 20-credit modules are split into two separate codes in the research questionnaires (right-most column) in order to obtain responses on the separate parts of the module. This 'split' will be clear and familiar to students completing the questionnaires as the classes are presented in this two-part format when delivered. Numbers in brackets after each class code give the number of responses to the agency perception questionnaire on which the given class results are based.

Year	Code	Class	Credits	Classes included in the study (with split codes where applicable)
1	CP101	Chemical Engineering: Basic Principles	20	
	CP102	Chemical Engineering: Fundamentals, techniques and tools	20	
	CH110	Chemistry laboratory	10	
	Various	*Foundation modules taught by Chemistry and Mathematics departments*	60	
	Various	*Electives taught by range of Faculties*	10	
2	CP203	Thermodynamics and Chemical Principles	20	CP203T (45), CP203C (45)
	CP204	Fluid flow and heat transfer	20	CP204F (47), CP204H (47)
	CP206	Chemical Engineering Practice 1: Laboratory Y2	20	CP206 (44)
	CP207	Process analysis and statistics	20	CP207P (45), CP207S (45)
	CP212	Process Safety	20	CP212 (45)
	CP213	Applied Maths	20	CP213 (45)
3	CP303	Materials, processes and applications	20	CP303S (36), CP303M (36)
	CP305	Ethics, sustainability and economics	20	CP305S (36)
	CP306	Design and Advanced IT	20	CP306 (37)
	CP307	Chemical Engineering Practice 2: Laboratory Y3	20	CP307 (36)
	CP315	Biochemical Engineering	10	CP315 (36)
	CP316	Reactors	10	CP316 (38)
4	CP405	Process control and environmental technology	20	CP405P (32), CP405E (32)
	CP407	Design Project	60	CP407 (32)
	CP409	Advanced separations and problem solving	20	CP409S (32), CP409P (32)
	CP414	Particle technology and advanced reactors	20	CP414P (32), CP414R (32)
5	18530	Chemical Engineering Project	60	
	Various	Optional specialist advanced classes, *eg* Programming, Molecular simulation, Safety Management, Petroleum Engineering, Clean Combustion, Frontiers of Chemical Engineering, Electrochemical engineering…	6 ×10 credits each	

2. Context and methodology

2.1. Context of the study

The University of Strathclyde BEng (Bachelor of Engineering) and MEng (Integrated Masters) Chemical Engineering full-time undergraduate (UG) degrees have an identical curriculum for Years 1–4, with MEng students going on to complete a Year 5 Masters year. (Four year/five year duration for BEng/MEng are typical in Scotland.) Both BEng and MEng are fully accredited by the Institution of Chemical Engineers (IChemE, 2020), the most recent renewal being in 2019/20. The average entry tariff (a 'score' based on an applicant's school-leaver qualifications) to the Strathclyde UG Chemical Engineering degrees is in the top quartile of institutions teaching the subject at this level in the UK (HESA, 2022). In practice 'home' undergraduate (students resident in Scotland) entry is strongly competitive since numbers are limited by a quota set by the Scottish Funding Council. An alternative entry route is available *via* the 'Engineering Academy' where students enter in Year 2, having completed a one-year preparatory course at a local Further Education College. In total, typical student intake is around 80 per UG year. Most students enter in Year 1 with typical total of 5–10 further students per year directly entering years 2–4, some of whom are from international partners under 'Memorandum of Understanding' agreements and attend typically until end of Year 4. The Department also recruits to a distance-learning based part-time BEng/MEng Chemical Engineering degree (cohort typically 20 per year), a range of full-time and part-time distance-learning MSc programmes (typically 30–50 per year), and a Degree Apprenticeship (typically 5–10 per year): for simplicity at this stage, since the learning contexts, experiential backgrounds and curricula of these programmes may differ substantially, our study focusses purely on the full-time UG cohort.

The full-time UG curriculum as of the time period of the reported research (2021) is detailed in Table 1. In general the curriculum is characterised by foundation subjects (chemistry, maths, introductory concepts of chemical engineering) in Year 1, core chemical engineering (fluid flow, thermodynamics, safety, process analysis, laboratory skills) in year 2, transition to design, operations and applications in year 3 (process design, reactors, separations, materials, sustainability, economics and ethics, applications laboratories), and advanced topics, skills and design in year 4 (advanced reactors and separations, process control, environmental technology, advanced problem-solving and the capstone group design project). Year 5 MEng topics include advanced safety management, programming and optimisation, simulation methods, and specialisms such as petroleum engineering, energy materials, combustion, advanced monitoring and measurement, and so on. Year 5 is completed by a one-semester Chemical Engineering Project with options for international study *via* Erasmus, workplace project with a partner company, or in-house project associated with one of the Department's research groups. (The work reported here is based on the outcome of such an in-house project, designed and carried out in Semester 2 of 2021 by one of us, SP, under the supervision of MDH.).

The period in which this work was implemented and data collected

(January-April 2021) coincided with the Covid-19 pandemic. In common with many other UK Universities, Strathclyde implemented an almost fully-online teaching programme for academic year 2020–21, consisting of recorded video lectures, interactive online tutorial sessions, remote video-based laboratories, remote group design and individual project supervision sessions. Additionally all assessments were carried out online. Teaching materials and assessments were delivered through the University's Moodle-based virtual learning environment, while the Zoom platform was used for interactive remote sessions. This differing context for the current year will be discussed below where relevant to results and observations.

2.2. Methodology

All methodology was designed in accordance with the University of Strathclyde's well-defined ethics policy on research involving human subjects, and was approved by the Departmental Ethics Committee acting on behalf of the University Ethics Committee, prior to commencement of the data collection. All participants were fully informed of the purposes of the study and the use the data would be put to, and the timescale over which the data would be processed before deletion. We took care to collect only data pertinent to the aims and expected analyses to be undertaken in the project (see 2.3.3 below), in order to comply not only with University ethical requirements but also with the principles of UK GDPR. All participation was voluntary and participants were expressly informed that their responses or participation could not have any impact on their academic outcomes. In the case of the questionnaires involving students from Years 2–4 (see 2.3.1 below) all data was collected anonymously. For students from Year 5, in order to facilitate connection between the agency questionnaire and the critical thinking study (see 2.3.2 below), students were asked if they would be willing to participate in the follow-up critical thinking study, and if so were asked to supply their email address as identifier. From this list of participant volunteers the researcher carrying out the critical thinking study (SP) arranged critical thinking interviews through which critical thinking questionnaire and verbal comment responses for each participant were collected. After this stage all recorded identifying information was deleted permanently from the questionnaire data. The critical thinking interviews were of necessity not anonymous to SP, but all data from them was recorded without recording identifying information, while meeting recordings were deleted permanently once transcripts were completed. SP did not share any identifying information with any other researcher involved or any other participant. Hence all data stored post-completion of the data collection stage were effectively anonymised. Data were stored on password-protected facilities accessible only by the researchers.

2.2.1. Agency in the curriculum questionnaire

The research project divides conveniently into two activities aligned with the Research Questions stated in Section 1.2 above. Firstly, an online questionnaire-survey consisting of Likert-type questions (Likert, 1932) on a 5-point scale was delivered by email to all current (as at January 2021) full-time UG students in years 2–5, *via* students' University email addresses. The questionnaire (Appendix 1) was designed to explore students' perception of agency across different modules of the curriculum to identify 'where' students perceived agency opportunities. In order to explore the applicability of Vaughn's 'dimensions' of agency (Vaughn, 2020) questions were designed around the three dimensions of 'motivation', 'disposition' and 'position'. Simple explanations of these concepts were given as part of the introductory material of the survey (Appendix 1). A score of '1′ on the Likert scale meant the respondent judged the class to provide low agency, a score of '3′ neither high nor low, a score of '5′ high agency, in the given dimension. Note that some 20-credit classes combine subjects under a single code, for instance CP204 Fluid Flow and Heat Transfer, but feature significantly different teaching approaches or topic areas and are delivered as separate blocks to students. Thus such modules were split in the questionnaire into separate items—CP204F for fluid flow, CP204H for heat transfer, in this example (Table 1). The survey was operated through the Qualtrics platform and was open for a total period of 5 weeks from week 6 to week 11 of the second (11 week) semester, corresponding to mid-February to end of March. Potential participants were sent email reminders twice during this time.

At the time of the study Year 1 students had experienced only one semester of teaching. Additionally the year 1 curriculum is in majority delivered by other Departments—Pure & Applied Chemistry and Mathematics & Statistics and other departments delivering a range of optional electives—and as mentioned above is not followed by Engineering Academy students. These factors led us to exclude Year 1 students from the study to avoid potentially adding in complex factors of variability.

Students in years 2–4 at the time of the study had experienced both on-campus and, following the shift to online teaching caused by COVID-19 in March 2020, online-delivered modules. In their current years at the time of the survey all teaching was delivered remotely through online platforms. Year 5 students, in contrast, had experienced *all* curriculum years 2–4 on campus *ie* prior to the pandemic. To limit some of the inevitable variation between different year cohorts' experience, and to enable at least basic exploration of potential variations between online and on-campus experience, the surveys presented to Year 5 and years 2–4 thus differed in their scope. Year 5 students were asked to consider classes from all their curriculum years 2–4 (all of which they had experienced on campus). Years 2–4 students were asked to rate *only* their current year's classes, *ie* all their included classes were experienced online, either in their previous semester (semester 1, September-December) or in their current semester. This of course does not provide a perfectly 'controlled' experiment regarding comparison, since Year 5 students experienced each class at a different time to the year 2–4 cohorts, but such differences are unavoidable: they will add to the intrinsic variability in the data, but a study that could fully control for all variables in students' experiences and examine all covariances is beyond our scope and resources. We return to this point in our discussion of limitations in Section 2.4.

2.2.2. Agency and critical thinking

To address the second research question, a smaller-scale more focussed approach was followed, concentrating on Year 5 students only. One of the researchers (SP) recruited voluntary participants from the Year 5 MEng cohort as described above, and interviewed each volunteer separately using online platform Zoom. SP, as a final year student carrying out this project as part of his curriculum, belonged to the same cohort as that surveyed in this second part of the study: it was felt that, based on previous anecdotal experience (Sharif, 2022), this aided recruitment of volunteers as well as, more importantly, giving participants greater confidence in engaging openly with the study. (Obviously SP himself did not respond to the survey.) Participants were asked a series of questions (Appendix 2) aimed at exploring Critical Thinking dispositions using SENCTDS as a starting point (Quinn et al. 2020) to which was added a question on 'knowledge and independent thinking' as described above. As well as asking for numerical scores, verbal comments were also sought pertaining to each disposition, as to why participants felt the given class encouraged or discouraged development of each of the critical thinking dispositions, in order to facilitate collection of a richer response that might illuminate interpretation of the numerical scores. Interview format was used as it was judged this would improve the verbal comment response rate.

While we could have asked the participants to respond to the critical-thinking survey for *every* class in the curriculum, it was felt this would be seen as onerous by participants; and in any case our purpose here was to explore not the wider question of critical thinking development across the whole curriculum, but specifically whether there is any detectable *correlation* between students' perceived development of their key critical

Table 2
Breakdown of agency survey participants in comparison to total cohort sizes in each cohort year. Students in years 2, 3 and 4 rated only their current year's modules (all of which were delivered online). Students in year 5 were asked to rate all their previous modules from year 2 to year 4, so that the maximum total number of responses for Years 2, 3 and 4 surveys were the given number under the relevant year plus the number under Year 5. Note that the actual number of responses for each given class could be lower than this maximum due to some respondents not including all classes in their response (*e.g.* compare numbers for year 3 classes in Table 1 with the maximum possible in this table). Due to resource constraints only Year 5 participants were invited to engage in the second-stage critical thinking study where questionnaire scores and verbal comments were obtained *via* direct interviews. Right-hand column gives the total cohort size for each year at the time of the study.

Cohort	Number of respondents (Agency questionnaire)	Critical thinking study (interview/questionnaire)	Total cohort size
Year 2	29		108
Year 3	20		86
Year 4	14		84
Year 5	18	12	70

thinking skills and their perception of agency opportunity in a learning activity. Hence, participants were asked to rate the contribution to their self-perceived critical thinking skills only from the two specific classes in the curriculum that they identified, in the first questionnaire exercise, as 'highest' in agency and 'lowest' in agency. Any strong difference in rating that correlated with this degree of agency would be an indication of at least a correlative link.

It might be thought there is potential for participants to deliberately rate critical thinking contribution from a class in a given way because they remembered they had already rated the given class as high or low agency. To minimise the possible impact of such bias, when participants were asked to complete the critical-thinking scale for a given class the class was not introduced directly as one they had rated 'low' or 'high' agency, but simply by its class code. Participants were not told that the choice of classes they were asked to rate was driven by their agency rating in the first questionnaire. The scales of the critical thinking measure do not directly reference the concept of agency, and every effort was made to avoid prompting participants to pre-connect the two elements during the interview discussions. While this does not completely rule out the chance of correlation bias it was felt that it was the best way to minimise such bias given the resources and context of the study.

2.2.3. *Demographics*

The breakdown of total participant respondents to the questionnaires and interviews, alongside the size of each student year cohort (years 2–5 as at January 2021) is given in Table 2. Beyond this information, we took the decision at design stage to deliberately avoid collection of any further demographic information on participants (such as gender, ethnicity, age, citizenship). This was for two reasons, one somewhat practical in terms of the scope of the initial study, and the other based on ethical considerations.

Firstly, while there is no question that demographic factors may have influence on students' experience, especially in the area of agency which is naturally related to the issue of power relationships (Goller and Paloniemi, 2017), we judged them beyond the realistic scope of what we designed as an initial exploration of agency perception in a chemical engineering degree. We feel such an initial exploration is valuable since agency is a topic that to our knowledge has as yet received little direct attention in the chemical engineering pedagogical literature. But undoubtedly, going beyond this work, questions such as the impact of gender and social background on perception of agency will merit serious consideration.

Secondly a condition for ethical approval of research at the University of Strathclyde is that data involving human participants should not be collected without serious intention to gain valuable knowledge and understanding by its analysis. Collection of demographic data which we had no planned intention of using would therefore be at odds with the ethical policy.

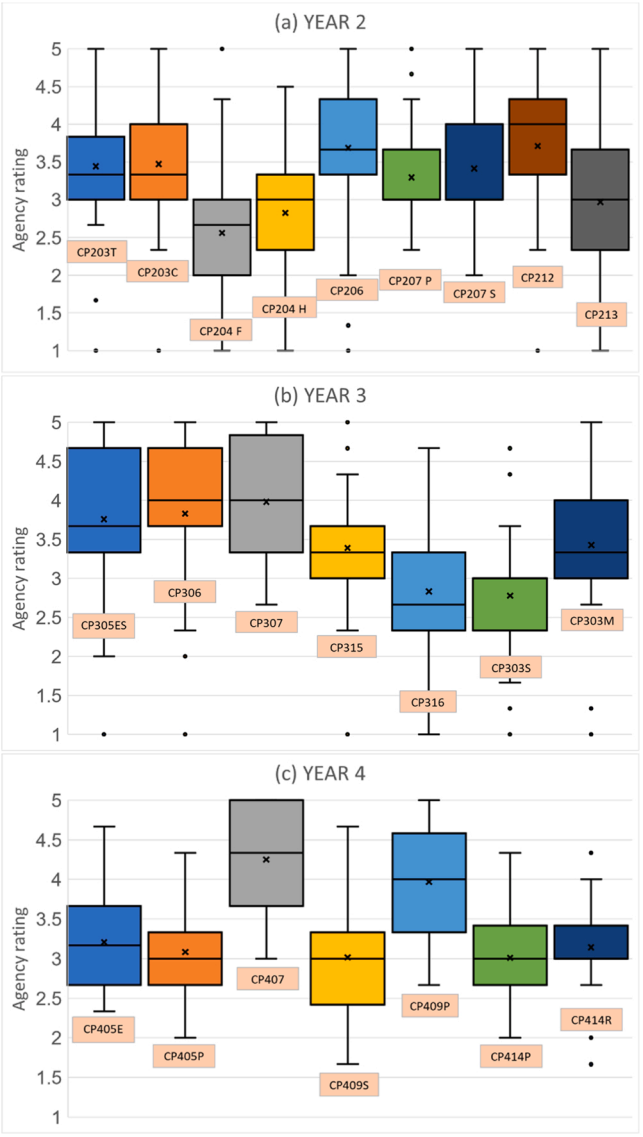

Fig. 1. Overall agency in modules in (a) Year 2, (b) Year 3, (c) Year 4. Refer to Table 1 for an explanation of class codes. For each survey response the agency rating shown is an overall average over the three dimensions (see text). Box plots show central 50 % range of responses with the mean indicated by a cross in the centre of the box. Whisker bars show the data range excluding 'outliers' (shown as isolated points) which are classed as data points > (1.5 x upper/lower quartile range) outside the central box.

The different year group cohorts invited to participate in the study are comparable in terms of admissions criteria, progression regulations, general cohort demographics (*i.e.* the known demographic breakdown of the cohorts invited to take part in the study) and curriculum studied year by year. The single difference between the conditions of study of the year groups is that the students in year 2 are subject to a different final degree grade weighting: their year 2 class marks will not contribute to their final degree whereas the year 2 marks of the students in year 3–5 at the time of the study contribute a total of 10 % to the final BEng/MEng degree grades.

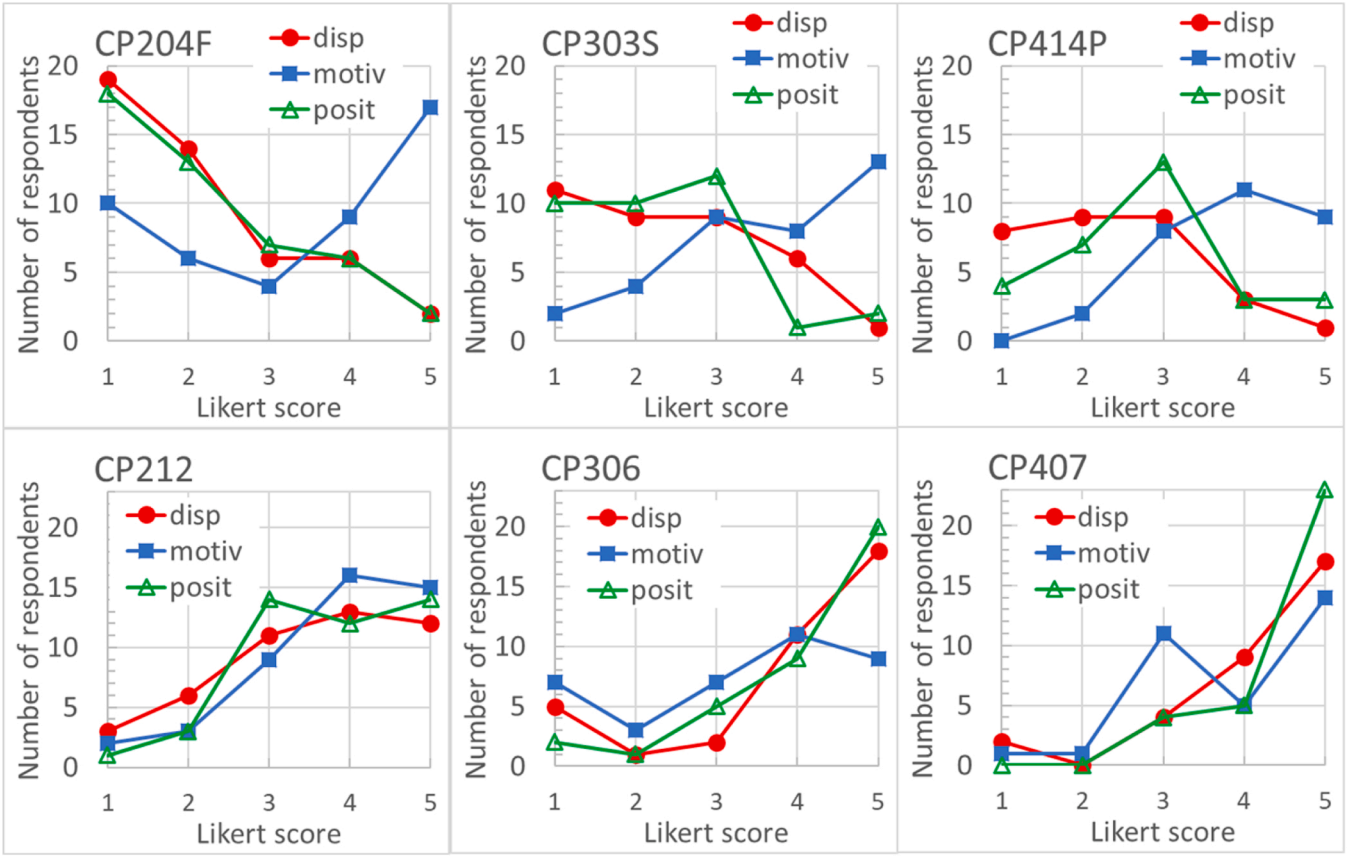

Fig. 2. Agency rating in the three dimensions defined by Vaughn (see text), contrasting example classes with lowest overall agency rating in each curriculum year (top row: CP204F, CP303S, CP414P) and classes with highest overall rating in each year (bottom row: CP212, CP306, CP407). Plots show number of respondents returning each Likert rating, where 1 =strongly disagree (that said dimension of agency is provided by the given class); 5 = strongly agree. Red circles: Dispositional dimension; blue squares: motivational dimension; green triangles: positional dimension.

2.3. Research limitations

As with any relatively short timescale/small cohort/single context study, our exploration is necessarily limited as to its sample size. We carry out some statistical tests as we present results but we also comment on observed trends even when we cannot confirm statistical significance. Our reasoning is that there has been limited previous study of the agency issue in chemical engineering education and one important role of a small-scale initial study is to highlight and focus possible directions for more detailed examination in further work. The wide diversity of student populations (Elliot, 1999) also fundamentally implies that we should be alert to sometimes small or limited phenomena or experience, rather than seeking only indicators that show strongly peaked 'mean tendencies'. We should at the same time be very aware, of course, of the dangers of extrapolating too far and assigning what might be limited features to whole populations. Furthermore, any observational work involving 'real' experience raises the problem of uncontrolled variables, complex environmental and personal factors that will have influence on individuals' experience. Thus while we raise various suggestions and possible issues as we discuss the results, we also summarise at the end of the paper areas where potentially important factors arising from this initial study would benefit from further investigation and clarification.

3. Results

3.1. Agency and the curriculum

A total of 81 respondents (Table 2) returned the curriculum survey, rating on a standard 5-point Likert scale the degree of agency they perceived in each of Vaughn's three 'dimensions' for each of a defined range of classes (Appendix 1; as described above, all classes in years 2–4 for year 5 respondents; only those classes in the respondent's current year for year 2–4 students). The number of respondents as a fraction of the relevant year cohort size was between 20 % and 25 %.

3.1.1. Overall agency

Fig. 1 shows a measure of overall agency perception in each class, formed from the average of the three individual dimensional ratings for each class. Note that different classes can have different credit weightings: the question of weighting ratings by credit weighting in the curriculum will be returned to below. We see a typically wide spread of responses for each class, reflecting an intrinsic variance of actual experience student-to-student: no single class receives exclusively high or low ratings. Nevertheless there are also differences class-to-class indicated by the 'central' population response (ie the interquartile ranges either side of the mean, the 50 % of the respondents indicated by the boxes in the plots). In year 2, the CP204F class shows 75 % of respondents rating it at 'neutral' to 'low' overall agency, compared to CP206 Chemical Engineering Practice 1 (laboratory class) with its 50 % central population rating the class clearly *above* neutral. In Year 3, CP307 Chemical Engineering Practice 2 (again, a laboratory class) and CP306 Chemical Engineering Design and Advanced IT (a majority project-based class) are rated noticeably higher than for example CP316 Reactors, a mainly lecture- and small-scale problem-dominated class. In year 4, CP407 Chemical Engineering Design Project received no responses below neutral, while CP409A Advanced Separations (a lecture/small-scale problem dominated class) clustered around neutral.

Table 3
Dimensional agency results comparing classes ranked lowest agency in each of years 2/3/4 and those ranked highest agency, across Vaughn's three agency dimensions.

Lowest overall agency classes				Highest overall agency classes			
CP204F Fluid Flow; CP303S Solid Mechanics; CP414P Particle technology				CP212 Process Safety; CP306 Design/ Advanced IT; CP407 Design Project			
CP204F	**Mean**	**Std Deviation**	**Count**	**CP212**	**Mean**	**Std Deviation**	**Count**
Dispositional	2.11	1.19	47	Dispositional	3.56	1.20	45
Motivational	3.37	1.59	47	Motivational	3.87	1.09	45
Positional	2.15	1.20	47	Positional	3.80	1.02	45
CP303S				**CP306**			
Dispositional	2.36	1.16	36	Dispositional	3.97	1.37	37
Motivational	3.73	1.20	36	Motivational	3.34	1.40	37
Positional	2.29	1.08	36	Positional	4.19	1.11	37
CP414P				**CP407**			
Dispositional	2.33	1.07	32	Dispositional	4.18	1.09	32
Motivational	3.90	0.91	32	Motivational	3.94	1.09	32
Positional	2.84	1.11	32	Positional	4.59	0.70	32

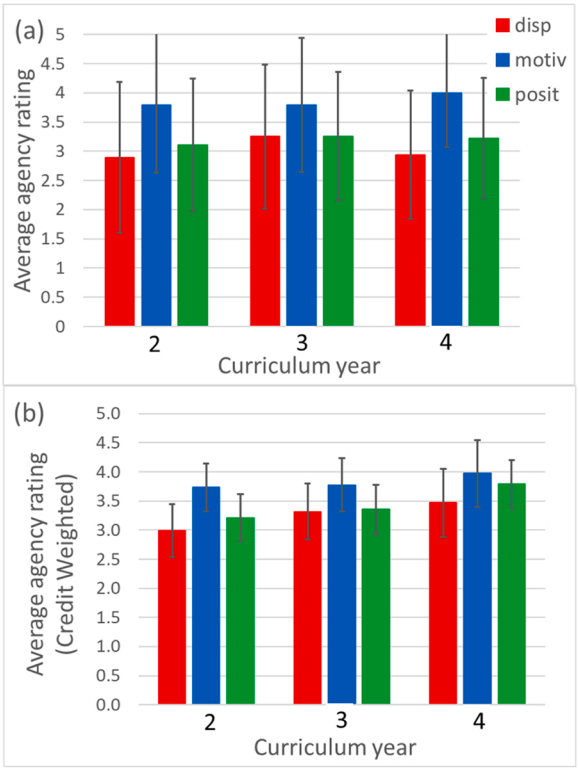

Fig. 3. (a) Agency perception rating averaged across all classes in each year, for the three dimensions of Vaughn's model: red = dispositional, blue = motivational, green = positional. Error bars show + /- 1 standard deviation of the mean. (b) Agency perception rating averaged across all classes in each year, with the average now weighted by credit value of each class in the curriculum. Error bars are + /- 1 standard deviation, calculated from variance of the weighted mean.

3.1.2. *Dispositional, motivational and positional dimensions*

As discussed above, each of the above overall agency scores was derived from a trio of separate ratings of agency in Vaughn's (2020) dimensions, for each class. For clarity here we focus on the pattern that emerges in these dimension scores in comparing classes rated overall as 'low agency' compared to those rated 'high' in each curriculum year. Fig. 2 shows the distributions of Likert ratings for the three low overall agency classes (top row) and for the three highest overall agency classes (bottom row) while Table 3 summarises relevant numerical data. We see a trend in the consistency of the various dimension distributions linked to whether classes are overall low or high rated. In low rated classes the major contributors to the low overall rating are high proportions of responses at 'strongly disagree'/'disagree' for the *dispositional* and *positional* dimensions. In other words, low overall agency classes are perceived as such due to students' judgement of low agency in disposition and position dimensions. Compare with high agency classes where the majority of respondents are rating all three dimensions of agency as high. Interestingly, in most cases for both low and high overall agency classes the motivational agency dimension tends to be rated high, the distribution peak being at 'agree' or 'strongly agree'. Therefore students tend to perceive all these classes to provide similar agency under the motivational dimension. If we interpret this dimension as illustrating students making choices and decisions associated with goals such as assessment, progression and qualification then this is perhaps understandable: anecdotally, a majority of students tend to be rather driven when it comes to grades and assessment outcomes, and this applies equally to classes that are dominated by lecture-driven delivery as to more project-based classes. The 'bimodal' outcome in CP204F Year 2 (a peak at 'strongly disagree' as well as 'strongly agree') may be driven by the fact that Year 2 grades contribute at most a total of 10 % to final degree grade under the University of Strathclyde's weighting system: we might expect then there to be a slightly weaker motivational effect or greater diversity across the cohort.

The positional dimension also shows a shift in distribution of responses with curriculum year of the class: in both low and high overall agency classes, the positional distribution shifts toward higher rating in later years. (For example, for the low agency classes in Fig. 2 top row, for CP204F the distribution is strongly peaked at score 1 *i.e.* 'strongly disagree' while for CP414 the peak has shifted to score 3 *i.e.* 'neither agree nor disagree'.) These shifts, whilst of course based on limited data, at least suggest consistency with the idea that as students become increasingly integrated into their learner community as the course progresses, and as the degree and 'importance' (as measured by credit value and assessment) of teamwork increases with curriculum year (see also 3.1.3 below), students also perceive an increased positional agency. For the example classes CP306 and CP407, there is in fact the strongest response on the positional dimension, consistent with the fact that these two classes are mostly or completely project-based with a large component of the work being carried out in design groups. Our data, while not statistically strong enough to 'prove' hypotheses, thus indicate some interesting further directions for exploring how group-based experience can provide agency (Lave and Wenger, 1991) and indicate some directions to explore if one wanted to build a detailed model of how different learning experiences could impact on perceived agency, for use in designing 'agentic curricula'.

Finally the dispositional rating distributions indicate the least variation with curriculum year alongside the greatest contrast between overall low and high agency classes. This suggests that this is a major factor in the overall agency rating, but also that perception of dispositional agency opportunity does not strongly evolve through the curriculum: high agency classes in all years are rated similarly under disposition, as are low agency classes. This may imply that there are

Table 4
Data for year-average agency ratings in the three dimensions of Vaughn's model, showing unweighted averages (ignoring the relative credit value of each class) and credit-weighted averages where each class is weighted in the year-average by its credit value (see Table 1 for credit values of each class in each year). For weighted averages, the standard deviation is obtained from the variance of the weighted mean where the variance of each measured class value is weighted by the square of the credit value as a fraction of the total credits in the year.

	Year 2		Year 3		Year 4	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Unweighted						
Dispositional	2.89	1.29	3.25	1.23	2.94	1.10
Motivational	3.79	1.15	3.79	1.15	4.00	0.93
Positional	3.11	1.13	3.25	1.10	3.22	1.03
Credit-weighted						
Dispositional	2.99	0.45	3.32	0.48	3.47	0.59
Motivational	3.73	0.41	3.77	0.46	3.97	0.57
Positional	3.21	0.40	3.35	0.43	3.79	0.41

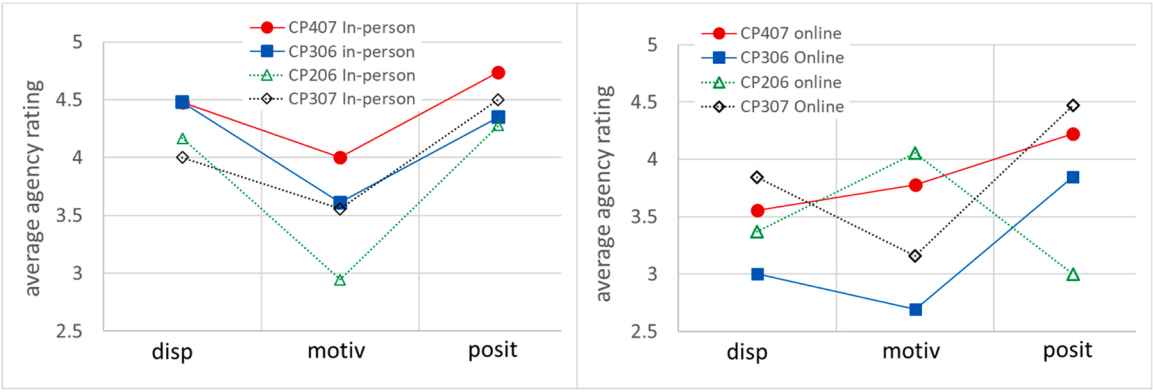

Fig. 4. Average agency rating in the three dimensions of Vaughn's model, for project-based and laboratory classes, comparing the responses from students who experienced the class in-person on campus prior to the COVID-19 pandemic (left-hand plot) with those who experienced it through online delivery after the pandemic led to campus closure (right-hand plot). CP306 and CP407 are design-based, group-based project-dominated classes (solid symbols), while CP206 and CP307 are laboratory classes (open symbols).

common factors across these classes that can give a class a high dispositional agency rating. it is worth observing that there *are* clear similarities in CP212, CP306 and CP407: the latter two are as mentioned above both design-focussed and group-based, while all three classes have a strong industry/application focus and a typically broad 'whole system' viewpoint, as opposed to a specialised technical or theoretical focus as might be found in topics such as fluid flow, mechanics and so on.

3.1.3. Trend in overall agency by curriculum year

A pertinent question is whether we can detect developing year-by-year trends over the curriculum, of the overall degree of agency that learners perceive themselves to be provided with by learning activities. Fig. 3(a) shows a 'raw' average of the Likert ratings from all questionnaire respondents, averaged over the classes in each year of the curriculum (see Table 4 for data). There is no clear trend here: however, if we weight the averages according to the credit value of each class (see Table 1) then as shown in Fig. 3(b), something of an enhanced trend of increasing perceived agency with curriculum year does appear, particularly in the dispositional and positional dimensions. Credit-weighting is a way, admittedly approximate and heuristic, of taking into account the varying amounts of time or effective 'workload' different classes represent, in order to arrive at a measure of 'total agency experience' for students as they move through the curriculum. An increased degree of apparent agency would certainly be consistent with the increasing degree of open-ended, deeper and more complex, 'whole system' problem-based work comprising the student experience year by year. The observed trend is weak and more data would help to clarify (it may also be questioned whether averages of Likert scores alongside 'spreads' measured by standard deviation can really be compared when distributions as in Fig. 2 are not at all symmetric about a mean)—but had we seen for example an enhanced trend in the opposite direction it would have at least called into question the *a priori* assumption that open-ended work is an important factor in providing agency.

3.1.4. On-campus and Online experience: project work and laboratory classes

By comparing the class ratings given by Year 5 students and those from students in years 2–4 we make a preliminary investigation of potential differences in agency perception for classes delivered on-campus as opposed to online. As explained above, Year 5 students had experienced all classes up to and including their year 4 on campus (prior to the pandemic), while Year 2–4 students were surveyed only on their current classes in their respective years, which were experienced online: so by comparing results from Year 5 respondents with those from Year 2–4, we can make a (relatively crude) comparison between online and in-person experience for specific classes. We stress that this is in no sense a 'controlled' comparison of online and on-campus experience since students' external situation was in many ways different prior to the pandemic compared to during it. Additionally we are asking Year 5 students to reflect on their previous experience up to two and half years ago and so 'recall' issues will further add uncontrolled variability—although carrying out a true controlled study by for example exposing half of a given student cohort to one experience and the other half to a different experience, simultaneously, would seem likely to raise ethical challenges. There would thus be many unconsidered variables in play in most study methodologies. Therefore here we comment only briefly here in two contexts where we might be most interested in examining the contrast between in-person and online experience, *viz.*

Table 5
Comparison of agency perception in project-based and laboratory classes, between cohorts which experienced the classes delivered online during the 2020–21 pandemic, *vs* cohort which experienced the classes in-person prior to 2020. See Table 1 for explanation of class codes. The statistics included show the results of a two-tailed t-test for difference in the mean agency rating (online experience *vs* in-person experience), in the three dimensions of Vaughn's model. The green cells indicate cases of significant difference in the means, at the 95 % confidence level, while the red cells indicate no significant difference at this confidence level.

Module	CP407	CP306	CP206	CP307
In-person:				
Dispositional mean (std. dev.)	4.48 (0.95)	4.48 (0.90)	4.17 (1.15)	4.0 (1.19)
Motivational mean (std. dev.)	4.0 (1.09)	3.61 (1.20)	2.94 (1.06)	3.56 (1.20)
Positional mean (std. dev.)	4.74 (0.54)	4.35 (0.78)	4.28 (0.75)	4.5 (0.71)
Online				
Dispositional mean (std. dev.)	3.56 (1.24)	3.0 (1.63)	3.37 (1.21)	3.84 (1.17)
Motivational mean (std. dev.)	3.78 (1.20)	2.69 (1.65)	4.05 (1.18)	3.16 (1.34)
Positional mean (std. dev.)	4.22 (0.97)	3.85 (1.57)	3.0 (1.20)	4.47 (0.70)
T-test statistics				
Significance Level, α	0.05	0.05	0.05	0.05
Degrees of freedom, v Dispositional	10.24	13.25	34.92	34.71
Degrees of freedom, v Motivational	12.43	15.81	34.12	34.01
Degrees of freedom, v Positional	8.61	12.81	23.64	34.75
Test Statistic, T Dispositional	1.70	1.95	1.74	0.35
Test Statistic, T Motivational	0.41	1.13	-2.69	0.74
Test Statistic, T Positional	1.61	0.72	3.58	0.16
From t-table, two tail test				
t(1- α)/2, v, T Dispositional	2.22	2.15	2.03	2.03
t(1- α)/2, v, T Motivational	2.17	2.13	2.03	2.03
t(1- α)/2, v, T Positional	2.28	2.17	2.06	2.03

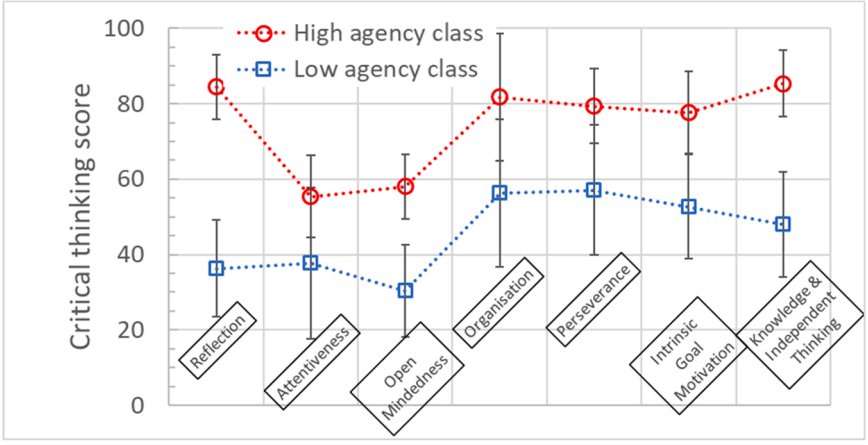

Fig. 5. Average critical thinking scores for classes rated as 'high agency' and for classes rated 'low agency' by individual Year 5 students. The critical thinking categories are shown by the text labels and the score is the average across the responses for each category, expressed as a percentage of the maximum possible score in that category from the questionnaire scales used in the Year 5 survey. Error bars are +/- one standard deviation.

group-based project work and practical laboratory classes. The online versions of laboratory classes (CP206 and CP307, Chemical Engineering Practice years 2 and 3 respectively) were delivered using recorded, filmed experiments carried out by laboratory staff: students were given the task of analysing and reporting on the data gathered as supplied to them *via* the virtual learning environment. The online project-based classes (CP306 Design and Advanced IT, CP407 Design Project) were facilitated using zoom-based group meetings and students had their own University zoom accounts enabling them to arrange their own meetings and group collaboration as well as lecturer-timetabled supervisory meetings.

Results are shown in Fig. 4 and Table 5**.** For the two project-based classes, CP306 and CP407, we observe a weak tendency for on-campus experience to be rated as higher agency than online in all the three dimensions of the Vaughn model, reflecting perhaps the greater sense of control and freedom to organise felt by groups working without pandemic restrictions (social distancing, closed campus, limitations of online collaboration). Results from laboratory classes (CP206 and

Table 6
(a). Averages of students' rating of how classes help respondents develop seven characteristic critical thinking dispositions (see text). The table compares respondents' critical thinking ratings of the class that each individual had rated lowest for perceived agency with critical thinking rating for the class that the individual had rated highest for agency. On the given scale each rating has a certain possible maximum score, as shown in the table: 'raw' average scores are given as well as averages as a percentage of the possible maximum (plotted in Fig. 5). (b) Results from two-tailed t-test for significant difference of the averages between the lowest-agency rated class and the highest-rated agency class, for each critical thinking disposition. The green cells show statistically significant difference at the 95 % confidence level (1-α), while red cells show no significant difference at this level.

(a)

Critical Thinking Disposition	Average score	STDev	Maximum Possible Score	% Average	% STDev
Lowest rated agency class					
Reflection	10.17	3.58	28	36.31	12.78
Attentiveness	10.58	5.62	28	37.80	20.07
Open Mindedness	8.50	3.43	28	30.36	12.24
Organisation	11.83	4.12	21	56.35	19.62
Perseverance	12.00	3.63	21	57.14	17.28
Intrinsic Goal Motivation	14.75	3.85	28	52.68	13.76
Knowledge and Independent Thinking	10.08	2.93	21	48.02	13.95
Highest rated agency class					
Reflection	23.67	2.39	28	84.52	8.54
Attentiveness	15.50	3.04	28	55.36	10.86
Open Mindedness	16.25	2.38	28	58.04	8.52
Organisation	17.17	3.56	21	81.75	16.93
Perseverance	16.67	2.09	21	79.37	9.98
Intrinsic Goal Motivation	21.75	3.06	28	77.68	10.92
Knowledge & Independent Thinking	17.92	1.85	21	85.32	8.79

(b)

Critical Thinking Disposition	Degrees of freedom, v	Test Statistic, T	t (1- α)/2, v, T
Reflection	15.22	-3.06	2.13
Attentiveness	12.87	-0.47	2.16
Open Mindedness	15.89	-1.89	2.12
Organisation	20.33	-0.80	2.09
Perseverance	13.41	-1.07	2.15
Intrinsic Goal Motivation	18.54	-1.27	2.10
Knowledge and Independent Thinking	14.39	-2.70	2.14

CP307) are less clear, with more varied differences between online and on-campus experience across the three agency dimensions. Interestingly therefore despite the obvious and intuitively 'significant' limitations of students not being able to carry out their own experiments in the online version, we do not find a *consistent* contrast in agency perceptions between in-person and online for laboratory classes. For example, for year 2 laboratories (CP206) we in fact find statistically significant differences in the mean agency ratings for the motivational and positional dimensions, at 95 % confidence level through a two-tailed t-test (Snedecor and Cochran, 1989): however the difference is in 'opposite directions' in the two dimensions, *i.e.* in-person experience rates lower for the motivational dimension but higher for the positional dimension.

3.2. Critical thinking skills and their correlation to agency perception

In this section we present results from the questionnaire and interview study involving participants from Year 5, exploring potential correlations between concepts of agency and critical thinking. We report first on questionnaire results and then discuss students' interview comments, where participants were asked to 'explain' what factors of their experience in the classes influenced their critical thinking scores under the various dispositional categories.

3.2.1. Critical thinking questionnaire results

To explore whether there was a correlation between students' perceived agency provided by a given class and the degree to which respondents felt the class contributed to a range of critical thinking elements as described above (Section 2.3.2 and Appendix 2), an average 'critical thinking' score across participants was obtained for each critical thinking category, firstly for the class that each participant had rated highest for overall agency, and secondly for the class that the participant had rated lowest. The averages are not therefore over a specific class, but over the range of various classes that participants rated their highest and lowest in terms of agency. Fig. 5 and Table 6(a) show the comparison between highest and lowest agency classes in each of the critical thinking categories. There is a consistent tendency for perceived low agency in a class to be associated with perceived lower contribution of that class to the participant's critical thinking skills, across all seven of the critical thinking elements we included in the questionnaire. From t-tests, statistically significant (at 95 % confidence level) differences between the means for low and high agency were found for two elements, *Reflection* and *Knowledge and independent thinking* (Table 6(b)).

3.2.2. Students' reflections from interviews

Students were asked, for their two considered classes (the low agency one and the high agency one) why they considered the class to discourage or encourage the development of each of the critical thinking categories. We consider in detail here only the two categories that reveal the biggest and statistically significant differences in score between highest and lowest agency classes *i.e.* 'reflection' and 'knowledge and independent thinking' (Fig. 5). A detailed textual analysis of students' comments will be returned to in a future publication: here we aim only to illuminate the critical thinking questionnaire outcomes and suggest fruitful directions for further analysis of the possible connections between agency and the more well-established critical thinking paradigm. We extract comments summarised in the next sections by a simple judgement of comments that are 'negative' about a given disposition's development (*i.e.* comments where an experience or activity is perceived to diminish the capacity to act with the given disposition) and those that are judged 'positive' (experiences which improve the capacity for the

Table A2
Critical thinking questionnaire.

Critical Thinking Disposition	Scenarios describing participant's approach within the relevant module (scored on 7-point Likert scale):
Reflection	When theory in the module is presented to me, I try to decide/establish if there is good supporting evidence.
	When faced with a decision, I seek as much information as possible.
	I gather as much information about a topic before I draw a conclusion about it.
	When I obtain any sort of result in the module, I ask myself what relation it has to the problem/theory.
Attentiveness (R)	When performing tasks in the module I feel easily distracted.
	When solving a problem in the module I find it hard to concentrate.
	In lectures and tutorials of the module I often miss out on important information as I am thinking about something else.
	When learning a new topic in the module I often daydream.
Open-mindedness (R)	Thinking in the module is not about 'being flexible', it is about 'being right'.
	Being open-minded about expanding knowledge in the module is less important than people think.
	When attempting to solve complex problems in the module it is better to give up fast, if I cannot reach a solution, to not waste time.
	When I believe I understand a given theory I do not dwell on understanding it any further.
Organisation	I make a list and manage my time for tasks I need to complete in the module and thoughts on each task.
	I take notes to organise my thoughts and expand on queries that I gather.
	I construct diagrams, graphs, tables to condense large amounts of information.
Perseverance	I persevere with a very difficult task in the module.
	Frustration does not stop me from finishing a problem that needs to be done in the module.
	I find it desirable and beneficial to keep going with a hard problem and reflect on it after completion.
Intrinsic goal motivation	I enjoy learning new information within the module that challenges me to think.
	I look forward to learning challenging things in the module.
	I enjoy solving challenging problems in the module.
	If material is initially too complicated to comprehend, I still find it enjoyable handling the material as it stimulates my curiosity.
Knowledge and Independent Thinking	I can comfortably have a conversation with someone about theory I have learned in class
	I find myself thinking about how theory in the module could be utilised in the real world/research.
	I feel confident on answers I have produced on my own from the theory I have learned.

disposition). Judgements of the comments were made independently by the two authors and only those where agreement is found are included below. Again we emphasise that comments were sought on the basis of those classes rated by the students as lowest and highest agency, so that, for example, 'low agency' comments from across the population of students do not refer to a single specific individual class, but to the (potentially differing) class each commenting student has rated low on the agency rating questionnaire.

3.2.2.1. Comments on 'Reflection'. Low agency class: The comments provided various reasons why students felt low agency classes failed to encourage reflection. These included that success could be achieved by memorisation, rather than deeper reflection ("you only have to memorise you don't have to properly learn"; "you weren't told the reasoning behind the theory; it was given to you to memorise for the exam"; "there was no need to reflect on any evidence about things I learned, I just learned information for the exam so would only reflect on tutorials to memorise"). Additionally the content, structure, demands and materials of the class were highlighted as not promoting reflection ("[there was] no view of applications until closer to the end of the module, I would have reflected more if there was at the start"; "[I was] not faced with decisions to make"; "so much theory [was] given by written notes, you didn't have to look any further"; "[I] go through notes and see what has been pre-determined [for] the coursework"). The intrinsic attitude or behaviour of the student was raised as relevant: "I just accepted whatever was presented to me"; "I don't reflect much because I believe the instructor teaching me is always right and the content is not personal"; "I tend to not learn material properly until 2 weeks before the exam. Then I start just understanding how to get an answer and not where the steps come from to get an answer." An interesting comment shows the complexity of the agency concept: "I would ask the help of others rather than finding evidence for myself". One could interpret this too as a lack of personal agency; but, alternatively, one could argue that there is agency displayed in the act of seeking help, indeed from 'others', not simply the obvious 'authority' represented by the teacher.

High agency: Asked to comment on why high agency classes encouraged reflection, students emphasised the importance of the content and materials being explicitly placed into a wider context: "reasoning for theory is given as well as… usefulness in the real world"; "a lot of the coursework had real life scenarios that initially provided evidence to theory presented, it became easier to establish supporting evidence later for any theory as there was already clarity of evidence". The role of challenge, *ie* where the student has to connect, fill in gaps, and research for themselves was also raised: "expanding on what I know and what was given to me was necessary to accomplish [the course goals]"; "some theory presented was patchy, so I had to reflect to an extent to understand it"; "such a broad topic … basically forced to gather as much evidence as you believed was necessary to back up the topic". That the route to completion and the outcome of the activity was not perceived as entirely closed or obvious was linked directly to the need for reflection: "it was easy to go down wrong avenues, so reflection was necessary to not jump to conclusions". One comment highlights the role of the 'personal': "'the nature of the class makes you have to think more about what you have to do personally; it's based on your own research".

3.2.2.2. Comments on 'Knowledge and independent thinking'. Low agency: Commenting on why and how the low agency class might influence knowledge and independent thinking, a perceived expectation of memorisation was once again raised: "I just memorised stuff, but didn't retain it"; "didn't need to put a lot of effort in to understanding so just memorised to pass exam"; "I couldn't do tutorials without the solutions so this made it easier to just memorise what I had to know, so that's possibly why I don't feel as confident on answers I would produce myself." This gap between what the student felt they could achieve and the provided solutions was one example raised where the existence of 'answers' was reported to discourage independent thinking: other comments also referenced confidence ("no tutorial answers were my own, they belonged to the instructor, so I wouldn't feel confident with my own answer that was different"; "only feel confident in answers because I'm copying answers provided to me but if I was to produce answer myself I probably wouldn't [feel confident]") and implied expectations of 'the right answer' ("any questions I had were not really considered as the solution we wanted was only to be what the instructor had presented.") Note that the *intention* of the lecturer would have been that the students attempted to solve the problems themselves: the students were not 'blocked' explicitly from taking agency in problem-solving. But the way materials are presented/perceived, such as a solution being seen as what the instructor 'wanted', has an impact on whether students seek to exercise agency.

A further comment makes a direct link between agency, confidence and the nature of the learning task: "the open-endedness and free will of this module make me feel less confident in work I have produced". Here a task has been designed to provide agency opportunity: but the

student's lack of confidence has led them to perceive the 'agentic' experience as negative. Designing agentic learning activities could have negative effects through damaged confidence, if students do not feel prepared: what sounds on paper a high agency class ("open-endedness and free will") is actually rated as low agency.

One final comment makes an interesting link to the degree of engagement: "theory was not intriguing enough to think about real world utilisation." This suggests that motivation arising from engagement with the content can play an important role in encouraging the independent, agentic thinking required of students to do their own work placing basic knowledge into a wider context.

High agency: Asked why they rated high agency classes as positive for development of knowledge and independent thinking, students returned to the theme of confidence but in a more positive light: "The time required in the module and the participation makes you more confident overall in what you think"; "there is uncertainty due to the free will of research, however because I became so invested, I was confident in what I learned"; "you are confident due to the time you have put into your work"; "I was aware that I could only be so [partially] 'right' in an area I was working on, so I actually gained confidence overall when justifying the knowledge, I independently learned." Contrasting with the above observation that provision of 'authorised' answers to problems could discourage students from exploring their own solutions, here the possibility of being partially wrong is explicitly connected to gaining confidence and independently learning.

The role of 'real world' engineering, with its uncertainty, breadth and depth of involvement, was returned to in other comments: "you knew you were never perfectly correct … but that was something you started to appreciate in the world of engineering"; "in a major project you learn a wider variety of information and you learn a lot about how useful you could actually be as an engineer and that sticks with you"; "[you] felt like an expert in a very specialised field because of how involved you were in it."

A final intriguing comment suggests how imposing a degree of agency—requiring students to propose their own approaches—might itself encourage the development of confidence in independent thinking: "I *required* confidence to continue with anything I had proposed" (our emphasis). This notwithstanding the above points that, conversely, 'free will' can make students feel *less* confident. This is a good illustration of the point made in the opening discussion, that agency and the capacity to cope with it are a combination of both the environment—such as the demands imposed on the student by the learning activity—and the student's own response, whether to embrace and gain from the requirement to develop confidence, or to suffer and lose, from the negative impact on confidence of a situation the student does not feel able to cope with.

4. Conclusions and further work

The study described provides a dataset exploring how a typical chemical engineering curriculum is perceived by students to provide agentic learning activities. The rather wide spread in student responses even to a single given class is indicative of the intrinsic variability across the student population, consistent with the wide literature on how agency perception depends on both the 'environmental' factors comprising a given class or experience, and the student's individual psychology. Nevertheless, comparing different classes and different curriculum years there are several trends and differences visible which are consistent with some 'naïve' expectations, such as that classes that are primarily project-oriented tend to be perceived as more highly agentic. The study, while small-scale, forms a useful starting point to focus further work on how learning experiences provide agency and how students respond, especially useful given the relatively limited attention agency has received in the educational literature in chemical engineering.

The diversity of the student population and the complex range of 'uncontrolled variables' influencing each student's perception and response mean that while we can draw some initial insights, undoubtedly further exploration is required to form a comprehensive picture of how chemical engineering education can promote student agency. Qualitatively our data indicate some factors and trends, such as that 'lecture' classes tend to be perceived as lower agency than 'project' or 'practical' classes, overall perception of agency tends to increase year by year through the curriculum, and there are potential correlations between agency perception and more established critical thinking dispositions. But of equal value is the indication these initial results provide of useful directions for more detailed study. For example, laboratory classes are perceived as providing higher agency, at first sight not unexpected given the less 'controlled' outcomes from experimental work: but it would be interesting to explore more deeply what *specific* aspects of laboratory experience provide the sense of agency, such as analysis of data or the fact that students collect their own data, since many aspects of the experiments carried out are in fact quite highly defined. Similar deeper examination is suggested by trends from other high agency rated classes such as CP305 Ethics, sustainability and economics and CP212 Process safety. Both of these include a higher degree of assessment by non-exam/test methods such as essay, blog and presentation; but arguably they also involve a higher degree of broad situational or conceptual as opposed to mathematical analysis, for example human factors in safety and ethics, and political and environmental factors in sustainability and economics. Which of these aspects provides the agency perceived by students?

In searching for a correlation between students' perception of the agency level of a class and their rating of how the class helps develop various critical thinking dispositions we do find a consistency across the dispositions explored: students judge the classes they (separately) rate as high agency as also providing better critical thinking development across all the dispositions we look at. Again there are statistical limitations but we also find statistically significant differences for two dispositions despite a small cohort. Students' verbal reasoning behind their critical thinking ratings illustrate some aspects that they feel impact critical thinking, such as whether classes promote memorisation and highly defined 'solutions'—quoted as negatively impacting critical thinking for the low agency classes—or whether they have the confidence to work and think independently, given as reasons for higher critical thinking rating in the high agency classes. A more detailed exploration would help educators connect learning activity and the way classes are presented more directly with both critical thinking and agency. The students' explanations of their ratings also indicate the complexity of agency in learning: being given too much agency (such as through very open-ended tasks) when a student does not have the confidence to deal with it can negatively impact on the perception of critical thinking development.

In the educational sphere, agency has tended to be discussed in the literal context of 'student choice': students given the scope to choose their curriculum, choose their favourite assessment method, even design their own classroom layout. While these ideas are important and innovative, they can present challenges when, for example, curricula are highly constrained by professional and/or accreditation requirements; when assessments are constrained by resources, time and employability-related issues such as cross-institution comparability and trust; and when physical realities in universities set limits on environment. Our approach in beginning to explore agency in chemical engineering education is that agency goes beyond a literal interpretation of student choice: the degree of agency provided by learning experiences depends on many factors, not just whether students have explicit choice. Our data begins to illuminate agency as a powerful, complex concept when considering the capacity for education to prepare students for more complex tasks in an increasingly complex, globally-challenged future.

One of the major issues which we do not consider here is how wider aspects of student identity interconnect with perceived agency. Factors such as gender, ethnicity and cultural and social background are critical

to where individuals are located in the power structures underlying a given society. Since the concepts of agency and power are surely intertwined, these issues certainly demand examination.

It is worth finally noting that the topic of agency in education is not limited to the student: for example Frost (2006) focusses on the role of *teacher* agency in educational leadership. Whether teachers have agency in how they promote learning is of undoubted interest in the context of professionalisation and accreditation considerations (Koster and Dengerink, 2008) and it would be interesting to explore, for example, to what extent teacher as well as student agency-related issues are considered by professional bodies when developing accreditations and standards. This is of particularly timely importance in an age of increasingly globalised educational policy (Sahlberg, 2011) and managerialism (Trowler, 2005), rapid technological developments such as online courses and artificial intelligence (Fletcher et al. 2021), and the political drive to 'monetise' education (Kwarteng et al. 2012, Belfield et al. 2018). We may face a future where teachers are not engaged, creative supporters of learning, but developers of formula-driven 'content'; and universities are not vibrant centres of independent, critical thinking, but 'platforms' through which that content is delivered to passive, receptive consumers—a *Netflix* education, as it were. What is the role of agency in such a 'delivery and consumption' focussed educational model? Would such content deliverers and content consumers have agency, and would such consuming help would-be engineers learn to cope with and act with the agency that a future of climate change and resource scarcity will demand? This is why we think exploring agency in education is important.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data statement

All data underpinning this publication are openly available from the University of Strathclyde KnowledgeBase: https://doi.org/10.15129/10f4ea00–34d4–4dd4-b4a7–5106bd8cdeff.

Appendix 1. Agency scoring questionnaire based on model of Vaughn (Vaughn, 2020)

Students were issued online questionnaires operated in the Qualtrics system. Each questionnaire included an introductory explanatory page, followed by Likert-scale choice options for each class relevant to the respondent. Questionnaire links were distributed by email *via* Departmental student lists categorised by year cohort, such that each cohort could be sent a link including only the classes relevant.

The introductory explanatory page was as follows:

What do I score modules on?

You are asked to score modules within the Chemical Engineering course based on the three dimensions of student agency, ***dispositional, motivational*** *and* ***positional.*** *The following definitions and examples should provide clarity on what these dimensions mean:*

Dispositional: *relates to experiences which provide opportunities for you to develop your own knowledge, follow your own purpose, which may also involve lecturers guiding your pre-existing intentions.*

Dispositional examples: *projects you work on based on material discussed in class; tutorials requiring you to direct your own learning.*

Motivational: *relates to experiences which provide you with motivation to make choices, persist with your efforts, overcome obstacles, achieve goals.*

Motivational example: *being faced with tests/exams, being set complex problems requiring motivation to reach solutions.*

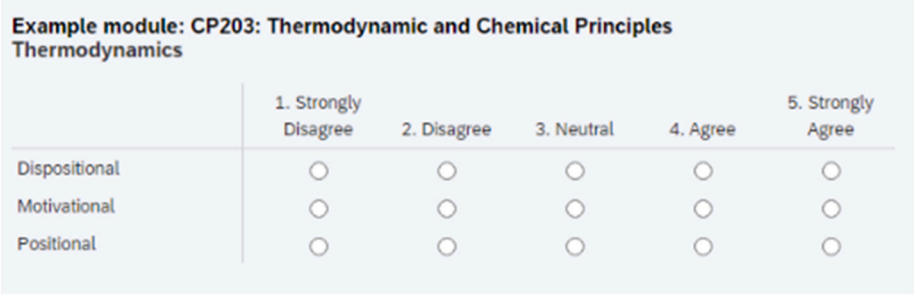
Positional: *relates to experiences which provide opportunities for interactions and negotiations, opportunities for you to take action to exert your influence.*

Positional examples: *working in a tutorial group where action can influence performance of the group, group choices.*

You will score each dimension according to the extent you agree/disagree that the said dimension of agency is present within your experience of each module, as follows:

1. Strongly Disagree / 2. Disagree / 3. Neutral / 4. Agree / 5. Strongly agree.

The introductory page also included as example graphic of what each question-block for each module would look like:



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Appendix 2. Critical thinking questionnaire

Participating volunteers completed the questionnaire during their online interview. The interviewer (SP) was present to aid with technical issues but made no other comments regarding participants' online responses. Responses were on a 7-point Likert scale:

1. Strongly Disagree.

2. Disagree.

3. *Slightly disagree*.
4. *Neither agree nor disagree*.
5. *Slightly agree*.
6. *Agree*.
7. *Strongly agree*.

Participants were directed to provide their scores on two modules, the modules they had previously scored lowest and highest in the Agency questionnaire (Appendix 1), with a score covering each scenario posed in the critical thinking scale as shown in Table A2. The various individual scenarios are categorised under the critical thinking dispositions as shown in the table. Some dispositions are essentially reverse-scored (labelled '(R)' in Table A2 although this is not indicated on the questionnaire as presented to the participant): for example, under 'Attentiveness', high scoring of 'When performing tasks in the module I feel easily distracted' would indicate lack of attentiveness. This reverse-scoring is inverted in calculating final average scores (Table 6) such that high scores indicate positive measure of critical thinking skills.

After scoring each disposition for the given class, the interviewer asked the participant to explain what it was about the experience in the class that they felt led to the given score. The response was recorded verbatim with no further questioning or clarification sought.

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