The Discovery Laboratory Part II: A Framework for Incubating Independent Learning

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Abstract

We have conceptualized the Discovery Laboratory at Imperial College London into an educational framework that enables independent learning among students. The study demonstrates an effective implementation of the framework with associated benefits for the learner in the areas of cognitive skills (creativity and critical thinking), metacognitive skills (ability to reflect on the entire learning process) and affective skills (adaptive motivation). Key supportive elements were transferring ownership of the learning process to students and incorporating assessment criteria that reward creativity. The framework can be easily adapted to other experiential learning contexts.

Keywords

Independent learning; critical thinking; adaptive motivation; metacognitive skills; enabling environment; transferability

1. Introduction

To successfully prepare chemical engineering students for the modern work environment, higher education providers must prepare their students for *independent learning,* which nurture important transferrable skills such as *independent thinking* and *creative problem solving*. Independent learning, as the process where "the learner, in conjunction with relevant others, can make the decisions necessary to meet the learners' own learning needs" (Kesten, 1987) consists of several internal and external components (Cukurova, 2014), which are visualized in **Figure 1**. The internal components include cognitive, metacognitive and affective skills of the learner, which we are taking together and terming reflective skills for the purposes of this work, whereas the external component refers to an "enabling environment" that includes the learning facility, time available, as well as peer and teacher/facilitator interaction.

Cognitive skills include critical thinking and creativity, both being the essential qualities for tackling problems in a rapidly changing environment. Amongst the wide range of definitions (Kazerounian and Foley, 2007), we have chosen divergent thinking as the basis of creativity in this study (Sternberg, 2006). Critical thinking is taken as "thinking self-correctively about one's own thinking …… (which) employs criteria and is sensitive to context" (Lipman, 1987). Both skills are essential for independent learning, as the former involves the generation of new ideas, whereas the latter involves assessing their respective quality (Treffinger et al., 2002).

Metacognitive skills are needed for the cycle of planning, monitoring and evaluation (Meijer et al., 2006), which is important for problem-solving. In this study, problem-solving is defined as the ability of designing, implementing and reviewing the solutions

to a specific technical problem. In particular, the ability to reflect on the learning process enhances the learning outcome (Boud et al., 2013), helping the learner to understand the reasons underlying his/her observations and to help change his/her action in a positive direction (Nguyen et al., 2014).

Affective skills enable positive self-regulation of emotions during learning (Vermunt, 1996). As the learner experiences set-backs more frequently during independent learning as compared to the traditional fully guided learning, one critical affective skill is adaptive motivation, which is the ability to self-motivate in the face of difficulties (Heyman and Dweck, 1992). The external factors that support independent learning can be termed broadly as an “enabling environment”, which include a proper facility, well-trained teachers and sufficient resources.

The Discovery Laboratory at Imperial College London is designed specifically for enhancing independent thinking and creative problem-solving through self-directed projects under the mentoring of subject experts (Chen et al., 2016). Students research one of eleven topics with the guidance of an academic supervisor, who serves as both subject expert and facilitator, thereby fostering a learning partnership with students (Magolda and King, 2004; Pizzolato, 2008; Pizzolato and Ozaki, 2007). An effective tutor must have both expertise in the subject matter and social congruence in order to achieve cognitive congruence with the students (Schmidt et al., 1993; Schmidt and Moust, 1995). Students learn in groups of four, as small groups promote collaborative learning, which improves the quality of learning via a number of social and cognitive mechanisms such as increased engagement and sharing complementary knowledge (Nokes-Malach et al., 2015; Springer and Donovan, 1999). Previous studies show that

this promotes the activation of relevant prior knowledge, which facilitates the acquisition of new information (Norman and Schmidt, 1992), and provides positive peer pressure that motivates the members to be diligent in meeting agreed deadlines (Schmidt et al., 2011).

This article describes our translation of these principles into practice by demonstrating the proposed pedagogical framework in the context of an experiential learning module, the Discovery Lab (Chen et al., 2016). We use a cohort level analysis to elucidate the efficacy of the proposed framework and tangibly demonstrate our implementation. These practices can be adopted by interested readers for any other hands-on learning activities in any engineering domain.

2. The Discovery Lab as a pedagogical framework for incubating independent learning

The Discovery Lab is a third-year chemical engineering module designed on the principles of Kolb's experiential learning cycle. Details of the approach, course context, workflow and its effectiveness as an experiential learning module can be found elsewhere (Chen et al., 2016). The typical stages of the Discovery Lab journey are shown in **Figure 2**. As also detailed elsewhere (Chen et al., 2016), the students have four days to critically review the literature, identify a research question and put together a draft research plan, five days to finalise the proposal, prepare risk assessments, and reserve/ request analytical equipment/ consumables. Students then have two weeks to execute their experimental plan for validating their hypothesis followed by a week to distil their findings into a report. Two weeks after report submission, the students were

interviewed. This is an intense process designed to develop senior students' intellectual and reflective abilities.

Timely feedback and support has to be provided at key stages to minimise the risk of failure while maximising independent learning. Figure 2 highlights these 'pinch points' in the students' learning journey where, for example, realistic research objectives have to be formulated based on available time and resources. Students tend to be overly ambitious here. The chosen feedback format is that of formative discussion with particular emphasis of debate in the actual lab setting. Project deliverables are a presentation and a mock manuscript based on publication guidelines from a well-known journal. The whole process is designed to provide students with as authentic a research experience as possible in the condensed timeframe.

As all projects are group projects with no assessment of individuals, students have to identify strengths and weaknesses within their group themselves which they also reflect on after the event in peer feedback. Students need to plan, communicate, negotiate, and collaborate with each other as well as departmental resources external to the teaching lab (e.g. analytical laboratories, mechanical workshop and even research labs) to deliver quality work on time. This not only strengthens them as independent learners, it also allows them to grow a professional network which may help them during their final year and beyond.

Figures 3 and 4 present a framework which can promote independent learning for any experiential learning modules. The colour coding of the different elements corresponds to the independent learning components in **Figure 1**, using the Discovery Lab as an

example. Additional details on various aspects of the course and how specific elements of the framework are translated into practice can be found in our previous work (Chen et al., 2016).

2.1 Internal Components

The internal components as outlined in **Figure 3** provide students with an opportunity to be creative and innovative when formulating an authentic research question. Students are required to consider the resources available and the constraints, i.e. consumables budget, limited modification to the equipment, and availability of analytical instruments, to come up with a work plan for validating or rejecting the research hypothesis. For an undergraduate level programme, such a semi-open-ended structure requires students to develop critical thinking. Students are in control of the project and have to solve problems/ adapt the work plan to achieve their objective, which mandates an enquiry based learning approach. Enquiry based learning is defined as “an approach based on self-directed enquiry or investigation in which the student is actively engaged in the process of enquiry facilitated by a teacher” according to the Higher Education Academy (Higher Education Academy, 2020).

Self-reflection is a key skill that students need to learn for any professional success. The Design-Analysis-Evaluation cycle provides that opportunity. Having meetings at appropriate intervals with the project supervisor provides a scaffold for the learner to evaluate results critically. Reward associated with changes to their work-plan based on their findings motivates students to self-reflect and changes their perception on negative results from failures to learning opportunities. Throughout the Discovery Lab journey,

students are particularly motivated to identify individual team members' strengths and how these strengths can aid the overall project outcome. Peer to peer communication is important to motivate struggling team members, and collective decision-making lifts the team spirit, thus achieving adaptive motivation, which is key to success.

Success in this context is not seen as 'finding the correct answer' but responding constructively to challenges through experimental adaptions. This creative thinking and problem solving is assessed throughout by the academic supervisor who as a subject area expert is best placed to make the correct judgement here.

2.2 External Components

The scaffolding in the project as outlined in **Figure 4** offers students a sandbox opportunity to pursue challenging targets with less risk of failure, therefore promoting cognitive skill sets, creativity, and critical thinking. The enabling environment can be realized by providing authentic research lab settings, and research grade equipment. A lab supervisor and a technician, who are knowledgeable in operational matters, provides an additional layer of support and informal sounding board for ideas, while maintaining the principle that students are always in the driving seat of their learning.

3. Research methodology

The extent of independent learning is reflected in the quality of the research work, which is assessed both formatively and summatively as discussed elsewhere (Chen et al., 2016). To understand the link between design intent (Discovery Lab framework) and implementation, as well as independent learning of external and internal components,

data and feedback at cohort level was collected through a course-wide survey and focus group. To avoid any influence or conflict of interest, these were designed and conducted by an independent researcher with no involvement in design, delivery or assessment of the module.

The survey was designed as a team activity, tested and refined prior to circulation. It had to capture the data we were interested in through comprehensively written questions. With respect to the focus group, students were recruited through emails which were sent to 3rd year Chemical Engineering student representatives for them to forward to their peers. 3rd year Chemical Engineering students, who completed the Discovery Lab module were recruited voluntarily for the focus group, on the understanding that their responses would be anonymised and that power relationships would be somewhat negated using a student researcher conducting the interviews. All participating students had attended all three lab based experiential learning modules (Foundation, Knowledge, Discovery) from first to third year of their studies. The pedagogy of these modules highlighting its influence on developing students as independent learners is described elsewhere (Chen et al., 2019). Even though the focus group is self- selected, it was made up of students who are representative of the cohort, for example a good gender balance and mix of ethnicities. As we made use of more than one methodological tool (surveys, focus groups and interviews) - to ensure a reasonable degree of triangulation, we were more readily able to ascertain when themes began emerging and when these were essentially repeating through our data analyses.

We are essentially exploring a singular phenomenon, investigative labs, in depth and detail which is our rationale for using the following methodology (Denscombe, 1998; Gray, 2004; Stake, 2000). Both qualitative and quantitative methodological tools can be used here (Mason, 1996), and we have applied both quantitative methods (student surveys) and qualitative methods (student focus group and interviews with the staff managing the lab). We used a mixed methods approach as we are interested in capturing detailed data on student perceptions and their learning gain throughout the course of the labs. In total, 31 students out of 108 students completed a survey, which was primarily aimed at establishing which factors influenced independent learning and to what extent this occurred. A Likert scale was used, enabling students to respond to statements (15 in total) from “strongly agree” to “strongly disagree”.

The statements used to form the survey were generated from applying Cukurova’s original framework, supporting independent learning, to the system we are currently developing in our lab setting. They are based on the “Student Interview Questions” in Appendix 5 (page 388 – 389) in Cukurova’s thesis (Cukurova, 2014). For example, question 1 in the original questionnaire *(“In what ways has the teaching on the Macromolecules course differed from the teaching on other courses?”*) was expanded into statement 1 to 4 in the survey with regard to the enabling environment (Figure 5) and statement 1 to 3 in the survey with regard to the reflecting skills (Figure 6).

The student survey contains a mixture of statements related to the organisation, structure and expected outcomes from the discovery lab, which essentially focus on the environment in which students are working (enabling environment), for example:

> *This project and peer assessment helped me to better know my strengths and weaknesses*

The skills and capabilities they feel they are developing (cognitive and affective skills) is reflected in:

> *I do feel more competent to conduct research, or manage my own projects as a result of this project*

Even though 31 students completed surveys, enabling us to develop meaningful insights related to student learning and development, we appreciate that this number represents a proportion of our entire student population. The survey was available on-line and could be readily accessed by all students in the third-year cohort (approximately 108 students), but in accordance with college ethics approval, students took part voluntarily and were not coerced into doing so. Hence the numbers were small. As we were primarily focused on attaining rich data, rather than a large volume of data, students were also given the opportunity to voluntarily participate in a focus group. The opportunity was advertised through the module leader and the group itself was moderated by an academic and a student researcher with no direct module association. Three students participated in a focus group session, during which three questions were asked:

1. What has been your learning journey through the discovery labs?

2. Are you able to comment on occasions where you used your creative skills and worked independently and authentically?
3. Can you comment on the support mechanisms in place?

The allocated time was one hour, however the end time was not enforced and the session ended naturally some time after this. With prior permission of the participants the session was recorded and the transcript was used to understand student perceptions about the learning process.

The discussion was free-flowing with plenty of opportunities for clarification and reflection before responding. As the students are not trained in social sciences, we did not expect them to differentiate between cognitive, meta-cognitive and affective skills. The link between their perception and these was established in the subsequent analysis of the transcript.

In particular, their comments highlighted how the Discovery Lab caters for different learning styles with a good balance between freedom and structure, which allowed them to take creative risks without constant stress regards the success and assessment of the project.

Admittedly, our findings reflect a specific situation in a specific time frame, although, due to the approach taken it has been possible to revisit Cukurova's work and propose a theoretical model accounting for learning gain in the labs and which can be tested and further refined. Equally, generalisability is problematic as the nature of a Discovery Lab experience refers to the specific rather than the general (Stake, 2000; Yin, 1981). However, we can adopt Bassey's stance on fuzzy generalisation here (Bassey, 1999) by accepting the premise that in a similar situation (resources, student numbers etc.) we

would expect similar findings. Indeed, as the Discovery Lab has been running successfully for the last ten years, the expressed sentiments from the students in the study correlate extremely well with informal and formal feedback received during that time.

4. Results

In terms of the results obtained from student surveys, the student focus group and staff interviews, we are presenting these under two major themes: 1) Enabling environment (external components) and 2) Skills (internal components). We appreciate that our specific results are somewhat limited. However, we are able to put forward some valuable insights based on the information we were able to collate.

4.1 External Components Necessary for Independent learning

Several of the statements related to the external components necessary for independent learning (**Figure 1**) have been grouped together to allow us to establish whether and how the teaching-learning environment created in the labs supports students in developing their independence.

The results as shown in **Figure 5** indicate that the labs were structured in such a way that, in order to achieve the learning outcomes students had to assume responsibility and adopt an independent approach to learning with 21 students strongly agreeing and 10 students agreeing with this statement. By working more independently, students also felt that they had greater freedom to make choices and explore options with 15 students strongly agreeing and 13 agreeing that they had freedom to make key decisions.

Students also had to rely on their team members to both achieve the end goal and to support them in developing their professional competencies. For example, 16 students strongly agreed, and 9 students agreed that team members supported one another in overcoming failures.

Additionally, student comments from the focus group reflected a decent level of independence from the teacher/instructor, whereby the student has taken personal ownership and responsibility (heightened use of the term 'I'):

> *I felt the scope was right for the two weeks that was in it. I had enough time to explore the problem. It was something I had not encountered before: It was protein aggregation and using self-interaction chromatography: that's not something we do a deep dive into. So, I had to do a fair amount of background reading. But it was appropriate, I could manage my time and fit it all in and plan my experiments*
>
> *Exemplar comment from student*

The academic lead for the labs, commented on the importance of creating an environment in which students can effectively work authentically as well as independently:

> *Discovery labs give students the freedom to think and the time, space and resources to apply that thinking to real-life research projects that they are going to perform. It gives them an authentic setting in terms of equipment, supervision and resources as a whole and they are pushed to finish things on time.*
>
> *Exemplar comment from academic lead*

4.2 Internal Components Necessary for Independent learning

A number of the statements related to the internal components necessary for independent learning (**Figure 1**) have been grouped together to allow us to establish whether and how students have developed their affective, cognitive and meta-cognitive skills through independent learning.

Data presented in **Figure 6** reflects three important ideas. There is significant agreement among students - 15 strongly agree and 10 agree, that they have developed confidence in being able to do things by themselves, and secondly that failure is an important feature of effective learning with 17 students strongly agreeing with this statement and 9 agreeing. Finally, students feel that they are developing skills of reflection and evaluation, which is key to their progression in terms of professional development with 16 students strongly agreeing and 13 agreeing that the set-up of the labs required them to make internal judgements and direct their work.

Students' comments from focus groups also reflect a growing confidence in their own abilities to conduct research as a response to having more independence and being able to direct the work the carry out:

> *I felt the project gave me the confidence to tackle research in a way that I may have been scared off before. I can see I developed an understanding of the approach to research problems. Like the process has been demystified … Especially someone who is not research inclined, in order to approach it, it made it easier to understand and at least have an introduction to it. Even at a high level, it was still useful to get access to it and break it down.*

Exemplar comment from student

The academic lead raised the importance and development of specific skills and capabilities (for example creative thinking, learning through failure) when they were interviewed as part of this research:

> *The point is that they learn how to make decisions in a safe environment where they can make decisions and fail in a safe space. This gives them confidence and the ability to think creatively and find deliverable solutions in a stress-free environment.*

Exemplar comment from academic lead

The data also presents us with some other interesting findings, namely that through this process of learning, students have started considering this notion of balance and what this might mean to their learning. For example, students have commented on working authentically in an exploratory way versus in a more contrived, instructed way, and between independency/peer support versus dependency on the teacher/instructor.

> *I think it was authentic if you were in the research lab. If you weren't, then I don't think it was. When you were in the group, you had the grad students helping you, it felt nice to be a part of the team.*

Exemplar comment from student

> *On the supervisor front, where there's the scheduled meetings, is it really necessary to provide that? Wouldn't it be more realistic for the students to schedule it instead. Surely the students will benefit from those meetings, but you*

shouldn't stipulate it. Leave it to their own initiative to seek that advice when it is more appropriate for them.

Exemplar comment from student

As highlighted before, we have offered the Discovery Labs since 2011 and through results complementary to this study we can prove the pedagogic effectiveness of the module. It is evident from **Figure 7** and **Figure 8** that the results of the student online evaluation survey (SOLE), which is a college wide survey to obtain student feedback (with participation rate approximately 80% of the cohort each year) correlate extremely well with our findings in this study as they reliably demonstrate robustness and effectiveness of this module over several years.

5. Discussion

From an analysis of our data, we have created a pedagogic framework (**Figures 3** and **4**) that demonstrates how the affective and reflective skills students develop are aligned with our specific and novel laboratory setting. Emphasis is placed on independence and creativity which are well established desirable skills for chemical engineers to acquire and can e.g. be acquired through mimicking an industrial scenario, the effectiveness of which has been reported elsewhere (Sharma 2011; Iborra et al. 2014). However, our model demonstrates how specific skills and capabilities can be grown as and when particular parameters change. For example, independency is actively enhanced when students are provided with fewer resources to carry out their experiments. It requires

them to be more resourceful, ask more questions and take greater ownership of their learning (Nolen and Koretsky 2018). Earlier definitions of independent learning (Meyer 2008) shifted us towards this idea that it is developed by students deciding what, when and how to learn, as well as developing an ability to inquire, both of which are at the forefront of the pedagogical design of the Discovery Lab. With respect to creativity, this goes hand-in-hand with independent learning (Jahnke et al. 2015) alongside a burning curiosity and a desire for producing original, new ideas. As students are granted the privilege of choice to work on something of interest to them, they are naturally intrigued by the subject area and the potential for new insights it offers. Our model is essentially one in which a tremendous amount of safe space within a negotiated teaching framework is available to the learner who can concentrate on independent thought and creativity.

6. Transferability

Having demonstrated the effectiveness of our approach, we would like to point out that it can easily be transferred to any experiential learning environment. The direct and straightforward step would be to simply adapt the Discovery Lab with different experimental projects suited to another programme of study while keeping the general outline and deliverables intact. A further modification would be to introduce different processes (‘D-Lab Link’) specific to the programme of study while mapping them using **Figures 3** and **4** to our pedagogic framework. This ensures transferability and equivalence of learning outcomes for the students in the new context.

7. Conclusion

The Discovery Laboratory at Imperial College London provides an educational framework that promotes independent learning among students. We have comprehensively demonstrated by analysis across the cohort the effective implementation of the framework and the corresponding learner dividends. Students acknowledge that the Discovery labs have provided them with an enabling environment and facilitated their skills development.

Through observations, surveys and focus groups, this study provides insight into good educational practices that enhance the internal factors of independent learning, which include cognitive skills (creativity and critical thinking), metacognitive skills (ability to reflect on the entire learning process) and affective skills (adaptive creativity). Giving the students independence to decide on their own research project enhanced creativity via a sense of ownership of the learning process. Incorporating assessment criteria that formally reward creativity also played an important role. By taking a facilitative role, the supervisor encouraged critical thinking amongst the students. Design-analysis-evaluation sessions during the experimental phase helped students to regularly reflect on their learning process and update their learning strategy accordingly, which enhanced their metacognitive skills. Students became better team players through adaptive motivation. These practices effectively enhance the various aspects of independent learning and can be adopted by other educators for experiential learning modules.

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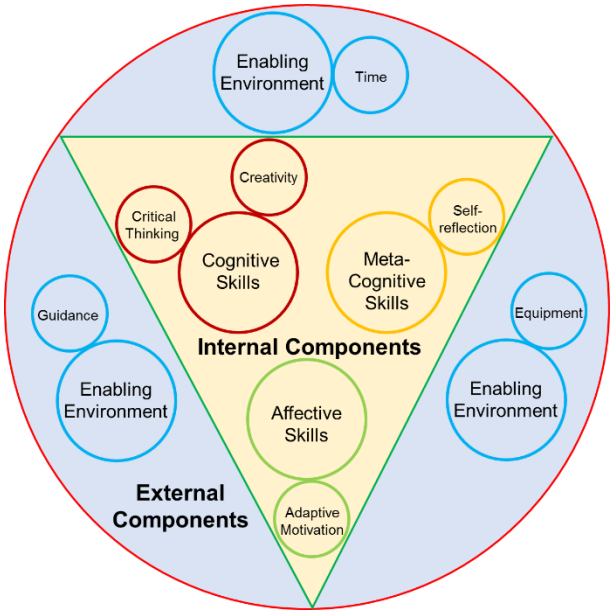


Figure 1: Necessary components for independent learning (learner perspective).

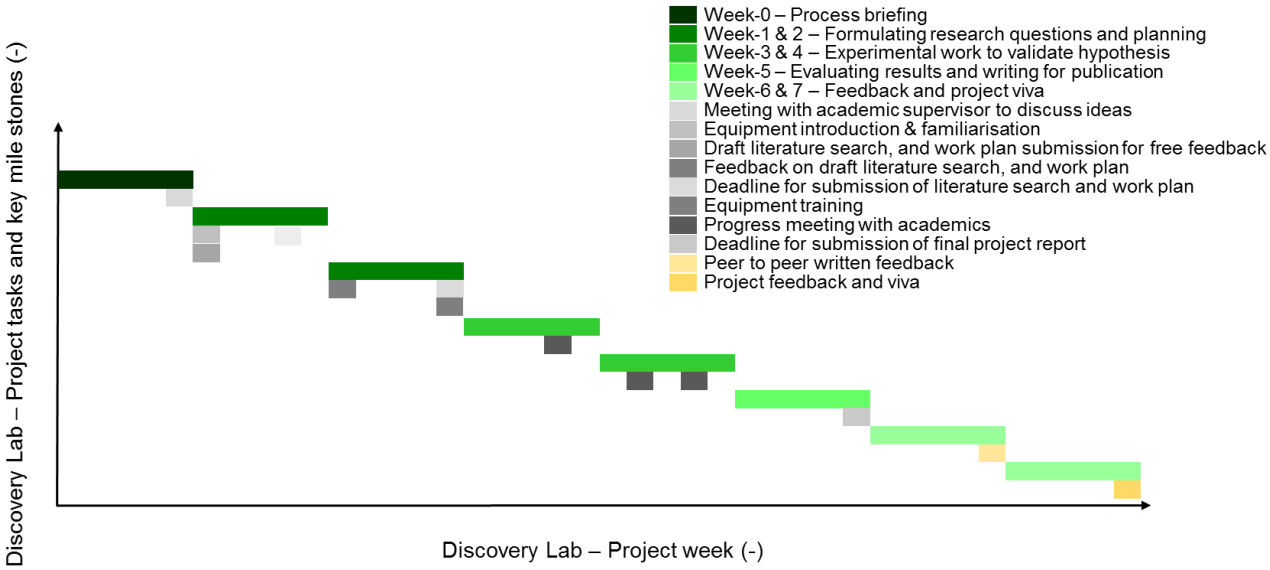


Figure 2: Discovery Lab – project time scale and key milestones.

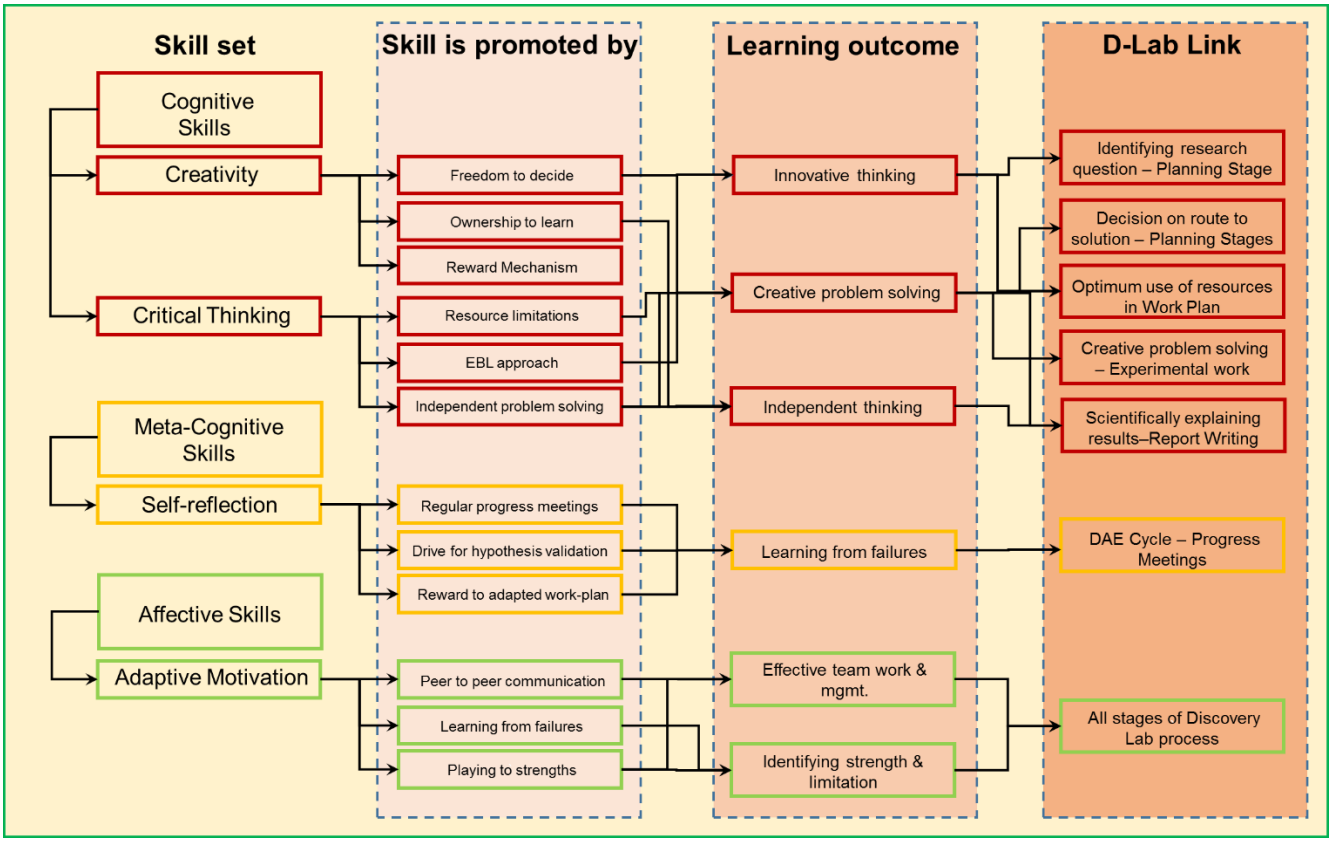


Figure 3 Internal components of Pedagogical framework for promoting independent learning.

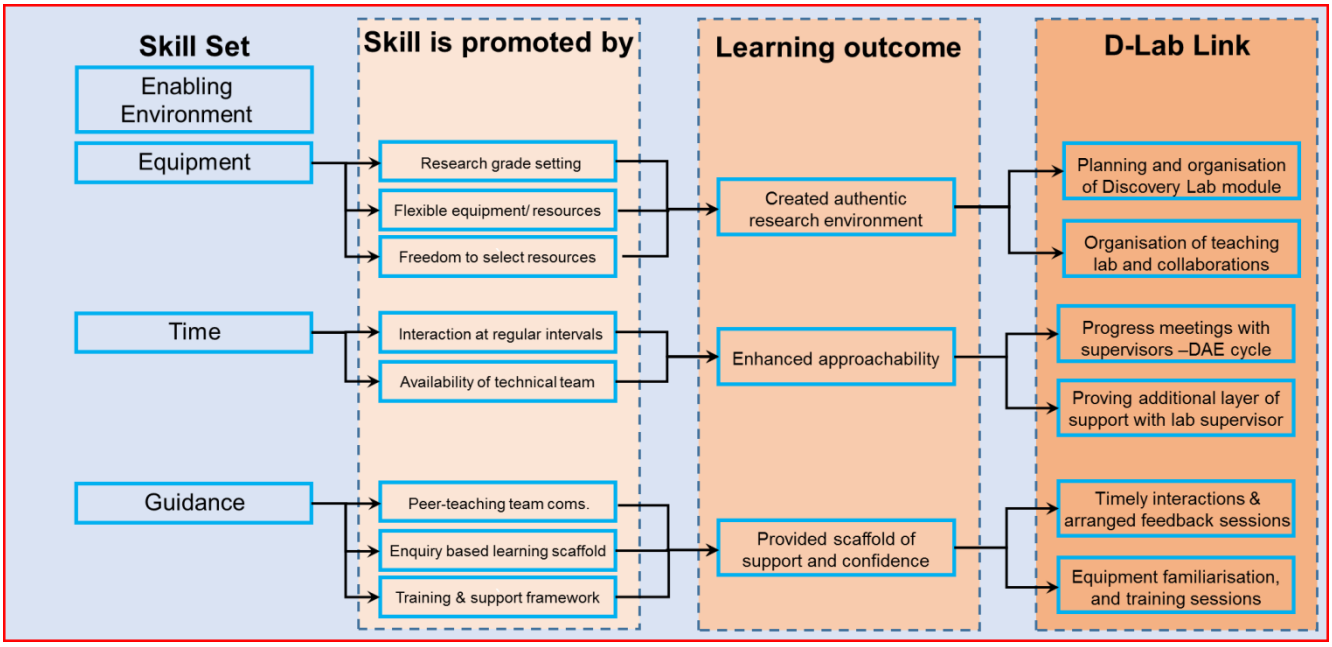


Figure 4: External components of Pedagogical framework for promoting independent learning.

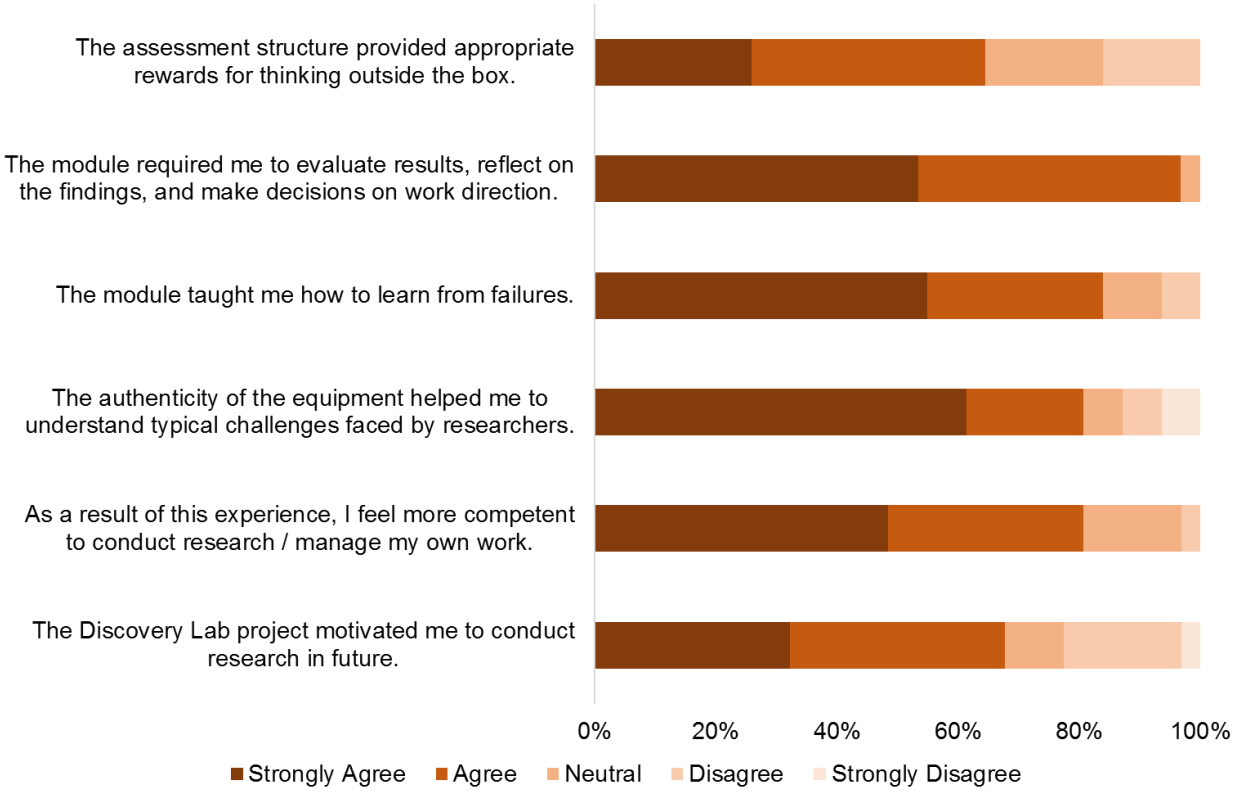


Figure 5: Student responses to statements relevant to external components necessary for independent learning



Figure 6: Student responses to statement relevant to internal components necessary for independent learning.

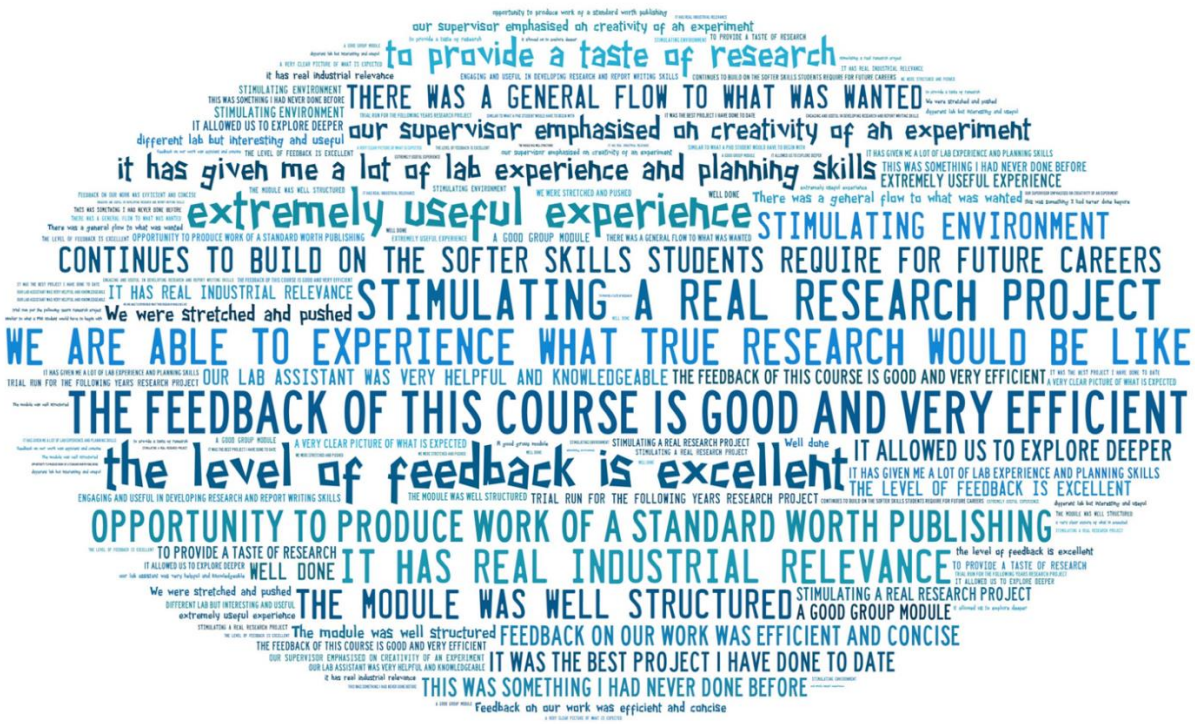
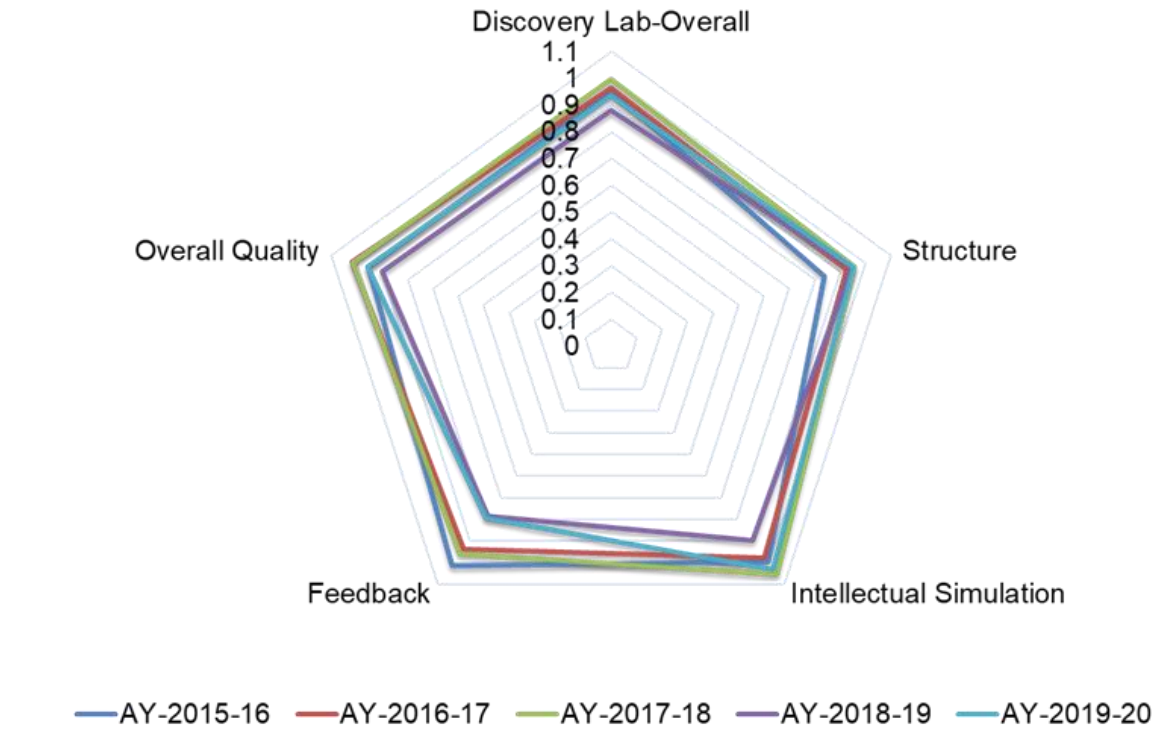


Figure 7: Word-cloud providing a snapshot of some of the student comments received for the Discovery Lab module from 2015.



> 0.9 – Well Done
- Share your experience

0.7 - 0.8 – Good effort
- Review feedback and make changes

0.5-0.6 – Room for improvement
- Review feedback and seek advise on how to improve further

<0.5 – Less than effective
- Need to re-think teaching strategy

Figure 8: Analysed quantitative results of module feedback from college-wide student survey.