Developing an Understanding of Undergraduate Student Interactions in Chemistry Laboratories

Wei, J. and Mocerino, M. and Treagust, D.F. and Lucey, A.D. and Zadnik, M.G. and Lindsay, E.D. and Carter, D.J.

Abstract

Laboratories play a crucial role in the undergraduate science curriculum and the effectiveness of learning in laboratories is influenced by learners' interactions with other students, the instructors, and the equipment used. In this study, a pre-lab survey was used to collect information about students' expectations of interactions in chemistry laboratories and how they can be ranked according to their importance. Post-lab surveys were used to capture students' perspectives about the frequency of interactions that existed in laboratory sessions they had completed. Direct observations of some laboratories were also conducted principally to validate students' self-reported interactions. The data were also sorted by three levels of student achievement in order to relate students' expectations of the importance of different interactions (pre-lab survey) and their self-reported frequency of interactions (post-lab survey) with their laboratory grades. Results from the pre-lab survey showed that Student-Instructor interactions were anticipated to be the most important ahead of conducting the laboratory activity, whereas results from the post-lab surveys showed that the most frequent interactions occurred between students. Students' self-reports (post-lab survey) and the direct observations agreed well suggesting that the post-lab survey is a robust tool for capturing the frequencies of student interactions in this and future studies. The results also showed that students gaining high grades both anticipated the importance of, and then engaged more frequently in, two-way communications with both students and instructors whereas students with lower grades placed a relatively higher reliance upon passive interactions such as the pre-lab briefing, the laboratory manual and internet sources. Finally, recommendations are offered to curriculum designers, instructors and students based on the overall findings of the study.

Keywords: Chemistry Laboratories, Laboratory Interactions, Laboratory Observation, First-year Chemistry.

Introduction

While most researchers agree that laboratory work is a vital component of the science curriculum, its educational value relative to the high cost has been frequently criticized (Hofstein and Lunetta, 1982;

Hodson, 1991; Johnstone and Al-Shuaili, 2001; Scanlon*, et al.*, 2002; Hofstein and Lunetta, 2004) Information from studies in laboratories is therefore required to distinguish productive from non-productive learning in laboratory classes and thereby create an effective learning environment (National Research Council, 2012).

In response to the call for an increased amount of research in laboratory settings, several studies have explored students' perceptions and their intended goals in traditional or reformed undergraduate laboratories (DeKorver and Towns, 2015; Galloway and Bretz, 2015a; Galloway and Bretz, 2015b; Chopra*, et al.*, 2017; George-Williams*, et al.*, 2018). Other studies have developed structured observation instruments to improve instructional practices (Lund*, et al.*, 2015; Velasco*, et al.*, 2016). However, only a few of the studies have focused on the analysis of student interactions and the relationship with their learning (Xu and Talanquer, 2013; Stang and Roll, 2014).

Interactions between individuals are an essential element in any social discourse and none more so for students in a formal learning environment such as a chemistry laboratory. While much research on laboratories has been focussed on the products of learning and skills developed and used by students, an important aspect of laboratory learning is understanding the interactions in which students engage when undertaking laboratory work. This then became the rationale for the present study where we sought to investigate the different types of interactions discussed below. This understanding can lead to the improved design of laboratory work, for example via the enabling and promotion of beneficial interactions or the better balancing of different interaction types during the activities undertaken by students.

Nature of Interactions in Science laboratories

Students may undergo different learning experiences and attain various learning outcomes even though they are provided with the same material, have the same instructor, and learn the same content in the same classroom, (George-Williams*, et al.*, 2018; Kousa*, et al.*, 2018). This finding suggests that students' learning may therefore depend upon their interactions during the laboratory activity; this hypothesis is at the core of the present study. Indeed, interactions in laboratories between students and their environment have a direct impact on learners' performance and their learning outcomes according to the theory of distributed cognition (Cole and Engeström, 1993; Nakhleh*, et al.*, 2003). In science laboratories, the environment can comprise elements such as other students, instructors, equipment, computers, and laboratory manuals (Cohen & Ball, 1999; Högström, Ottander, & Benckert, 2010). Accordingly, the main interactions between the learner and the environment in science laboratories can be classified into four categories (Moore, 1989; Sutton, 2001):

1) Student-Student (S-S) Interactions, which refer to interactions among students within or between groups;
2) Student-Instructor (S-I) Interactions, which refer to interactions between students and the instructor;
3) Student-Equipment (S-E) Interactions, which refer to students manipulating equipment such as glassware, using chemicals, consulting the laboratory manual, or accessing the Internet in the laboratories; and
4) Indirect/Vicarious interactions (I-I), which refer to students learning by observing others or listening to others' conversations.

The first two types of interactions (S-S and S-I) are both interpersonal and occur in two-way communication whereas S-E and I-I are one-way in face-to-face laboratories because students only take in information from these materials and may not receive instant responses.

The effectiveness of the four types of interactions in science laboratories has different research approaches. Studies of S-S interactions were mostly case studies, involving detailed analyses of students' behaviours in groups (Krystyniak and Heikkinen, 2007; Xu and Talanquer, 2013). Analysis of the S-I interactions considered their frequency and the initiators of the conversation (Stang and Roll, 2014; Lund*, et al.*, 2015; Velasco*, et al.*, 2016). Analysis of S-E interactions identified introductions to the equipment and how to use equipment to complete tasks but less on the frequency of interactions and their effect on learning outcomes (Tofan, 2009). Studies of indirect interactions relate to distance learning rather than face-to-face laboratories (Sutton, 2001; Kawachi, 2003). Despite this general recognition of the importance of interactions, research has not yet been conducted to connect these student interactions with learning outcomes. Thus, in this study, we seek to characterise the importance and frequency of these four types of interactions (S-S, S-I, S-E and I-I), as well as their relationship to students' achievement levels in the laboratory activities.

Measurement of Interactions in Science laboratories

Multiple tools have been used to capture and analyse student behaviours in science laboratory classes: interviews with participants (Högström*, et al.*, 2010), classroom observations (Xu and Talanquer, 2013; Velasco*, et al.*, 2016), and analysis of audio and/or video recordings (Krystyniak and Heikkinen, 2007). These tools are used to improve students' learning experiences or learning outcomes or to understand teacher behaviours and their use has largely been applied to the development of instructional practices (Egbert, 1991; Sadler*, et al.*, 2011; Stang and Roll, 2014).

Direct observation is a useful method to identify "what people are actually doing" (Bernard and Bernard, 2012) and when conducted in a structured way, observations can provide richer and more reliable information (American Association for the Advancement of Science, 2013). Existing structured observation protocols are described as being holistic, segmented or continuous (Hilosky*, et al.*, 1998; Sawada*, et al.*, 2002; Sadler*, et al.*, 2011; American Association for the Advancement of Science, 2013; West*, et al.*, 2013; Velasco*, et al.*, 2016). All of these observation protocols have been proven to be capable of showing specific interactions in laboratories. However, all of the protocols focus on reform, or how to improve, instructional effectiveness, not on the learners' actions, behaviours and interactions. Even though some student behaviours are recorded in the observation protocols described above, the data are insufficient to characterise the students' learning behaviours. The present study attempts to fill this gap by developing a new protocol with observation sheets to describe the frequency of various interactions from the viewpoint of students.

On the other hand, observations are time-consuming and may not be applicable in certain circumstances. Thus, in this study we principally used self-reporting to collect data on the frequency of interactions in first-year chemistry laboratories. Self-reporting using surveys have been used a great deal in distance education to characterise students' thoughts and perspectives about their learning processes (Sher, 2009; Kuo*, et al.*, 2014). Surveys have the advantages of their suitability for collecting large amounts of data and being a viable way of understanding participants' opinions. However, there are some concerns that surveys may be too subjective to present a reliable result (Mega*, et al.*, 2014). Accordingly, observations were used as an objective source of information to confirm the validity of student's self-reported survey data.

Theoretical Framework

The overarching goal of the research presented in this article is to design a meaningful learning environment for chemistry laboratories. In pursuit of this aim, we modified and used a framework derived from the Model of Educational Reconstruction (MER) (Komorek and Kattmann, 2008; Duit*, et* *al.*, 2012) to guide the research method (Figure 1). In this model, based on a constructivist epistemological position (Phillips, 2000), the learning environments, student perspectives, and course content are interrelated and influence each other. In other words, the MER model in Figure 1 integrates three lines of educational research (Duit*, et al.*, 2012):

- The investigation of students' perspectives of a given activity – in this case their perspectives about the ranking and frequency of interactions in the laboratory
- The clarification and analysis of the science subject matter – in this case students meeting the intended laboratory learning outcomes on laboratory principles and techniques, as measured by their marks
- The design of the learning environment – in this case the chemistry laboratories and the experimental equipment and materials with which the students interacted.

In this model, this integration allows consideration of students' perspectives of the interactions that not only improve researchers' understanding of the laboratory learning processes but also increases an understanding of the principles and techniques of the laboratory work being taught and learned. Based on the results of the analysis, the laboratory environment, the curriculum, or the design of the laboratory activity can be reconstructed.

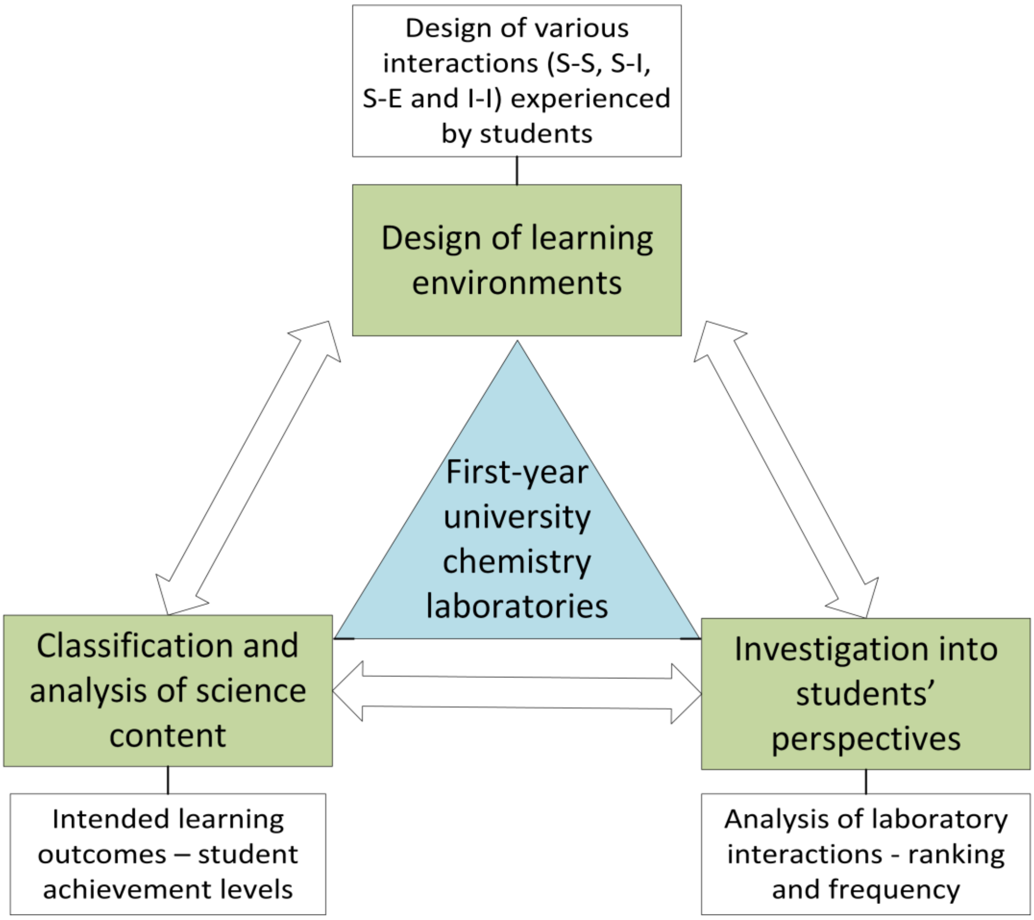

Figure 1 Theoretical Framework derived from the Model of Educational Reconstruction (Komorek and Kattmann, 2008)

*Note: S-S = Student-Student, S-I = Student-Instructor, S-E = Student-Equipment, and I-I = Indirect.

Research Questions

The goal of this study is to understand the importance and frequency of interactions in face-to-face chemistry laboratories that include student-student, student-instructor, student-equipment, and indirect interactions. The research questions guiding the study were:

1) What do undergraduate students consider to be important interactions for effective learning in introductory chemistry laboratories?
2) What type and range of interactions do students engage in during face-to-face laboratory work?
3) What is the relationship between patterns of student interactions and students' grades for the laboratory activity?

Results from the pre-lab survey were used to gather students' ideas about the importance of interactions; post-lab surveys and observations were used to gain information about the frequency of interactions, from students' and the observer's views, respectively. Further analysis using data from the pre- and the post-lab survey was implemented to answer question 3.

Methods

Participants and description of the laboratory

This study was undertaken in a first-year introductory chemistry laboratory class in a globally multicultural comprehensive Australian university. The students were from two separate laboratory classes in the Department of Chemistry, taking chemistry as a minor while majoring in Biology. The students' chemistry background was very limited; most had not studied chemistry in high school and a few who had studied chemistry, failed their examinations.

Laboratory sessions were conducted fortnightly, having a length of three hours each session, and included four different types of laboratory activities, namely, principles of measurement, intermolecular forces - solubility in liquids, quantification of acetic acid in vinegar and standardisation of hydrochloric acid (HCl) with a standard solution of sodium carbonate (Na_2CO_3). The learning outcomes were designed to build practical skills, combine practice and theory, as well as improve communication and teamwork abilities.

The structure of all laboratories had similar patterns: a pre-lab exposition conducted by the instructor describing key principles, highlighting laboratory procedures or possible hazards, and explaining briefly the data-analysis procedures. Students were then randomly assigned into groups (mostly in pairs, with a small number of three-person groups) before proceeding to use the laboratory equipment, analyse data, and answer the questions in the laboratory manual. While the students were working, the instructors would check their pre-lab questions, answer students' questions, and observe the whole class. Although the laboratory was scheduled to last three hours, students could leave early if they had successfully completed all the activities. Students' results were evaluated before they left the laboratory.

The pre-lab exposition process involved the instructor talking and the whole class listening, occasionally with one or two students answering the teacher's clicker questions. This form of student-instructor interaction happened between the instructor and all the students; there were far fewer one-to-one student-instructor interactions or indirect interactions.

The laboratory manual was the key resource for students. Before the students entered the laboratory classroom, they were required to answer the pre-lab questions relating to laboratory safety or specific concepts in the laboratory manual, ensuring that they had read the laboratory manual and done some pre-lab preparation. In the laboratory class, students would follow information about procedures from the lab manual, write down data, do further analysis following instructions in the lab manual, and answer relevant questions in the lab manual.

Data collection

After obtaining permission from the Human Research Ethics Committee (HRECs), two main forms of data collection, namely surveys (both pre-lab and post-lab) and direct observations (Bernard and Bernard, 2012) were used to provide a triangular description of laboratory interactions. Pre- and post-lab surveys were based on students' self-reports (Herrington and Nakhleh, 2003). The pre-lab survey was administered just once before the beginning of the first lab whereas the post-lab survey was administered after each lab class. Observations were made of all laboratory sessions during the semester. Of course, in any laboratory it is not possible to observe all students all the time. To eliminate any bias, the focus of the observations was not on any particular student or student group; rather by walking around the laboratory, a general sense of student interactions was recorded. The observer did not provide feedback to the students or instructors during the observation process.

The students' behaviours were not affected by being observed. The reasons are as follows. At the beginning of the first class, the observer informed the students that she would be unobtrusive and try not to interfere with their laboratory process. She also informed them that she was not an instructor and could only answer project-related questions if they arose. During the observation process, the observer always stood in the corner instead of closely behind a group of students. In addition, because the students' chemistry background was not strong, they focused on the laboratory process, having no time to consider the observer.

Survey forms and observation recording

Survey forms and the laboratory observation sheet were designed as follows. Research-group members first discussed the possible interactions as a group and then made their own lists of candidate interactions. Based upon laboratory observations conducted by group members, a single version of the survey forms and laboratory observation sheet were refined through discussion informed by results from studies in the literature. From the distance education literature (Moore, 1989; Sutton, 2001), with adaptations to be more suitable for face-to-face laboratories, interactions were differentiated according to four main items from the students' perspectives: Student-Student, Student-Instructor, Student-Equipment, and Indirect interaction. Details of these are presented in Table 1.

Table 1. Interaction Types, Interaction Categories, and Sources

Interaction type	**Interaction category[3]**
Student-Student (S-S) verbal interaction[1]	• Talking about lab procedures/equipment • Analysing data • Talking about basic concepts
Student-Instructor (S-I) verbal interaction[1]	• Talking about lab procedures/equipment • Analysing data • Talking about basic concepts
Student-Equipment (S-E) interaction[1]	• Engaging with lab procedures/equipment • Analysing data • Engaging with basic concepts
Indirect Interaction (I-I) [2]	• Observing other students' behaviours • Listening to other student-student conversations • Listening to other student-instructor conversations

[1] (Moore, 1989); [2] (Sutton, 2001); [3] (Sadler*, et al.*, 2011)

The pre-lab survey was designed to capture students' thoughts and perceptions about the importance of laboratory interactions before they began the work in the laboratory guided by the manual. A single means of collecting ranking items was used. In the pre-lab survey, we asked the students whether or not they agreed with their laboratory marks being used for our research analysis. Most students chose 'yes', while a few chose 'no'. We then only used the data from those students who allowed their laboratory marks to be used. This is why we have fewer participants when addressing research question 3. As shown in Table 2, thirteen possible kinds of interactions were listed and students were asked to choose the five most important items and rank them from 1 to 5 in order of descending importance.

Table 2: Pre-lab Survey Form showing possible laboratory interactions

Example interaction		Rank
Talking to another student you learn	..... about the procedures/lab equipment	
	..... how to analyse your results	
	..... about the basic science theory behind the lab	
Talking to a lab instructor you learn	..... about the procedures/lab equipment	
	..... how to analyse your results	
	..... about the basic science theory behind the lab	
During the prelab you learn	..... about the procedures/lab equipment	
	..... how to analyse your results	
	..... about the basic science theory behind the lab	
Reading the laboratory manual/notes you learn	..... about the procedures/lab equipment	
	..... how to analyse your results	
	..... about the basic science theory behind the lab	
You learn about the basic science theory behind the lab by using the internet on a smart device		

The post-lab survey was used to collect students' self-reporting of the frequency of their interactions after they had just finished the laboratory work. In this survey, as shown in Table 3, a list of possible interactions that may have occurred in the laboratory class was provided, similar to the pre-lab survey, but with some minor differences. Students were asked about their reflections on the frequency of different components of the four main kinds of interactions. In each item, students circled whether they thought they had exhibited this specific behaviour "never", "a few", or "many" times. The reason that we chose to use this kind of differentiation as opposed to ranges with numbers, such as "less than 5 times", was because it was hard for the students to count or remember the actual number of times that they had engaged in the types of interaction.

The Laboratory Observation Form shown in Table 4 was based on the development of one observation tool – the Laboratory Instructional Practices Inventory (LIPI) (Sadler*, et al.*, 2011) and was informed by research on the collection of interactions between teaching assistants and students (Stang and Roll (2014). The first author of this article acted as an observer recording verbal interactions and students' non-verbal expressions such as their gestures and watching other groups. A behaviour was recorded as a type of interaction irrespective of how long it lasted. A new activity was recorded if the students changed that activity or were interrupted. For example, students analysing data, even if it lasted several minutes, was considered as one activity but if students stopped analysing data to answer another person's question, it was considered that a new activity had begun.

Inter-observer Reliability (IOR) was assessed through the development process. Before the study reported in this article observation, the observer and another member of the research teamwent to several first-year chemistry laboratories to conduct preliminary data collections. They watched the same groups of students and conducted independent observations. IOR was calculated by Cronbach's alpha using SPSS, and the calculations were based on the agreement of coders of the same behaviour in the observation sheet. Cronbach's alpha had achieved a median of 0.70 (range 0.64 and 0.76).

Table 3: Post-lab Survey Form showing possible laboratory interactions

1. (***Student-Student Interactions***) **Did you talk to another student about ...**	**Never**	**A few times**	**Many times**
1.1 the procedures, protocols or lab equipment?	1	2	3
1.2 the basic science concepts behind the lab?	1	2	3
1.3 analysing your results?	1	2	3
1.4 discipline topics not directly related to the lab?	1	2	3
1.5 topics not related to the lab?	1	2	3
2. (***Student-Instructor Interactions***) **Did you ask the instructor about ...**			
2.1 the procedures, protocols or lab equipment?	1	2	3
2.2 the basic science concepts behind the lab?	1	2	3
2.3 analysing your results?	1	2	3
2.4 discipline topics not directly related to the lab?	1	2	3
2.5 topics not related to the lab?	1	2	3
3. (***Student-Equipment Interactions***) **Did you ...**			
3.1 read the lab manual/instructions associated with this lab?	1	2	3
3.2 use the Internet for technical assistance, data analysis or for concepts behind this lab?	1	2	3
4. (***Indirect Interactions***) **Did you learn by observing someone else's interactions in the lab, such as ...**			
4.1 observing another students experimental setup or behaviour	1	2	3
4.2 listening to a student/group of students asking another student for help/advice	1	2	3
4.3 listening to a student/group of students asking a teacher for help/advice	1	2	3

Table 4: Lab Observation Form

With Students	
... lab procedures, protocols or equipment	
... analyse their results	
... discipline science concepts	
... topics unrelated to the lab	
With Instructors	
... lab procedures, protocols or equipment	
... analyse their results	
... discipline science concepts	
... topics unrelated to the lab	
Indirect/Eavesdropping	
... another student asking a student	
... another student asking a teacher	

The focus of direct observations was on the nature of verbal interactions. Compared with the post-lab survey, items of nonverbal interactions, especially those related to using the laboratory manual, were not included because there were too many nonverbal behaviours in the laboratory, such as setting up the apparatus or walking around to find some glassware. Although these were by necessity omitted, student-apparatus and student-manual interactions occurred with a high frequency according to the observations.

Pilot study

A pilot study to assess the validity and reliability of the data collection tools was implemented by collecting data from three science and engineering laboratory classes during semester 2, 2015 (Carter, *et al.*, 2015; Treagust, *et al.*, 2016). After the pilot study, students' opinions were sought and subsequent improvements were made to the original survey forms. For example, the pre-lab survey was changed from a Likert scale for each item to the current form because students tended to assign each item as very important and were therefore difficult to ascertain the relative importance of the interactions.

Results from the pilot study showed that, even though there were minor differences, the students in science and engineering classes had similar expectations about the importance of interactions in laboratories; in addition, students had similar self-assessments about the frequency of their occurrences. We were thus confident that the instruments could be generalised as one easy-to-manipulate tool to collect student-interaction information in both science and engineering laboratories. Furthermore, the findings of this study and unpublished results from our group which were proceeded after the pilot study also had high consistency, giving us assurance that the instruments are reliable to present validated results (Wei*, et al.*, 2017).

Data analysis

We used figures to illustrate: (1) ranking of interactions in the pre-lab survey; (2) frequency of interactions in the post-lab survey; (3) frequency of interaction in the laboratory observation sheet; (4) ranking of interactions sorted by student academic levels; 5) frequency of interactions by student academic levels (Robbins, 2013).

To achieve (4) and (5), we classified students into three levels according to their final laboratory marks. These marks were combined with their individual marks and their laboratory test examination scores. We classified the students with a laboratory grade of 85% or more as the highest achieving students; students in the 70%-84% range as the middle-level students; and lower than 70% as the lowest achieving students.

Results

Ranking of Interactions - results from the pre-lab survey

To respond to Research Question 1, students' expectations and perceptions about the importance of the different kinds of interactions which may be helpful for their learning were collected. Student rankings of the importance of potential laboratory interactions are shown in Figure 2.

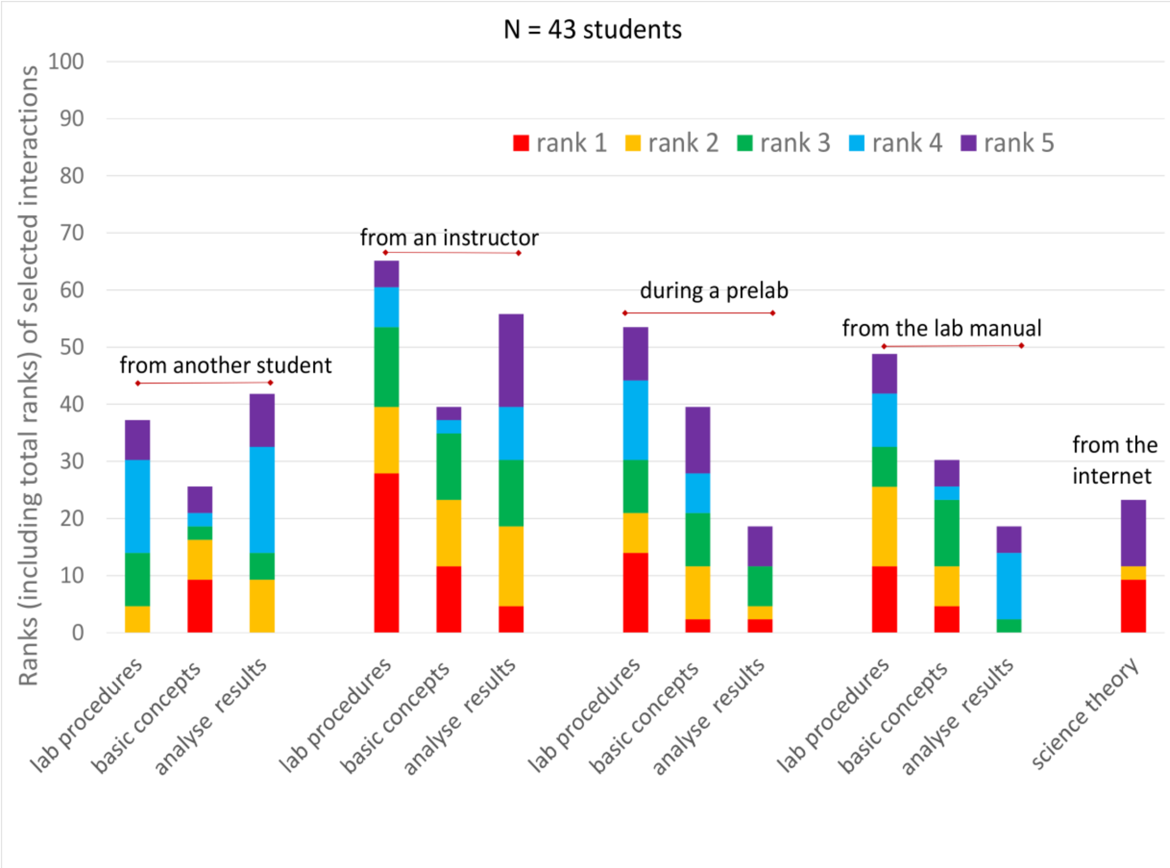

Figure 2 Student expectations of the importance of the potential interactions sorted by task types before undertaking the laboratory: Data obtained from the pre-lab survey (total number of selections = 45 x 5 = 215).

Combining ranks 1, 2, 3, 4 and 5 together, before they began to do the laboratory, the highest total of the ranks indicated that students thought that interactions from an instructor would be the most important. Twenty eight of the 43 students considered that they would ask the instructor about laboratory procedures, while 24 out of 43 and 17 out of 43 students expected that the instructor would help them with analysis of results or address theoretical concepts, respectively. Interactions relating to laboratory procedures were ranked as having the highest importance, across all of student-instructor, pre-lab, and student-lab manual interaction categories.

Of all of the interactions, the students thought that the prelab demonstration or laboratory manual would be the least important interactions to help analyse results. This is reasonable because in the pre-lab exposition the instructor mainly talked about procedures and concepts while the laboratory manual focused on procedures and sometimes concepts. Overall, the instructor was expected to be the main source of information as opposed to the other students.

Frequency of Interactions

Results from the post-lab survey

Both self-report and direct observations were implemented to respond to Research Question 2 – frequency of interactions. The post-lab survey results presented in Figure 3 show that students thought that they had communicated more frequently with their peers than with the instructors. They chose the item 'analysing results with other students' as the most frequent behaviour (around 60%) while talking about procedures with each other was the second highest (approximately 54%). Students also reported that referring to the laboratory manual and discussing basic concepts with other students (40% and 35%, respectively) were higher than all of the interactions with instructors (lower than 30%). Both the frequency of interactions with instructors and the indirect interactions had a relatively lower percentage. Overall, the most frequent interactions occurred between a student and other students. It should be noted that there were more responses in the post-lab survey compared with the pre-lab survey because the students needed to complete the post-lab survey at the end of each class, while they only did the pre-lab survey once at the beginning of the sequence of laboratories. Several items were not included here because of their low value; these were 'topics not directly related to the laboratory' (#1.4 & 2.4 in Table 3) and 'topics unrelated to the laboratory' (#1.5 & 2.5 in Table 3) (both S-S and S-I).

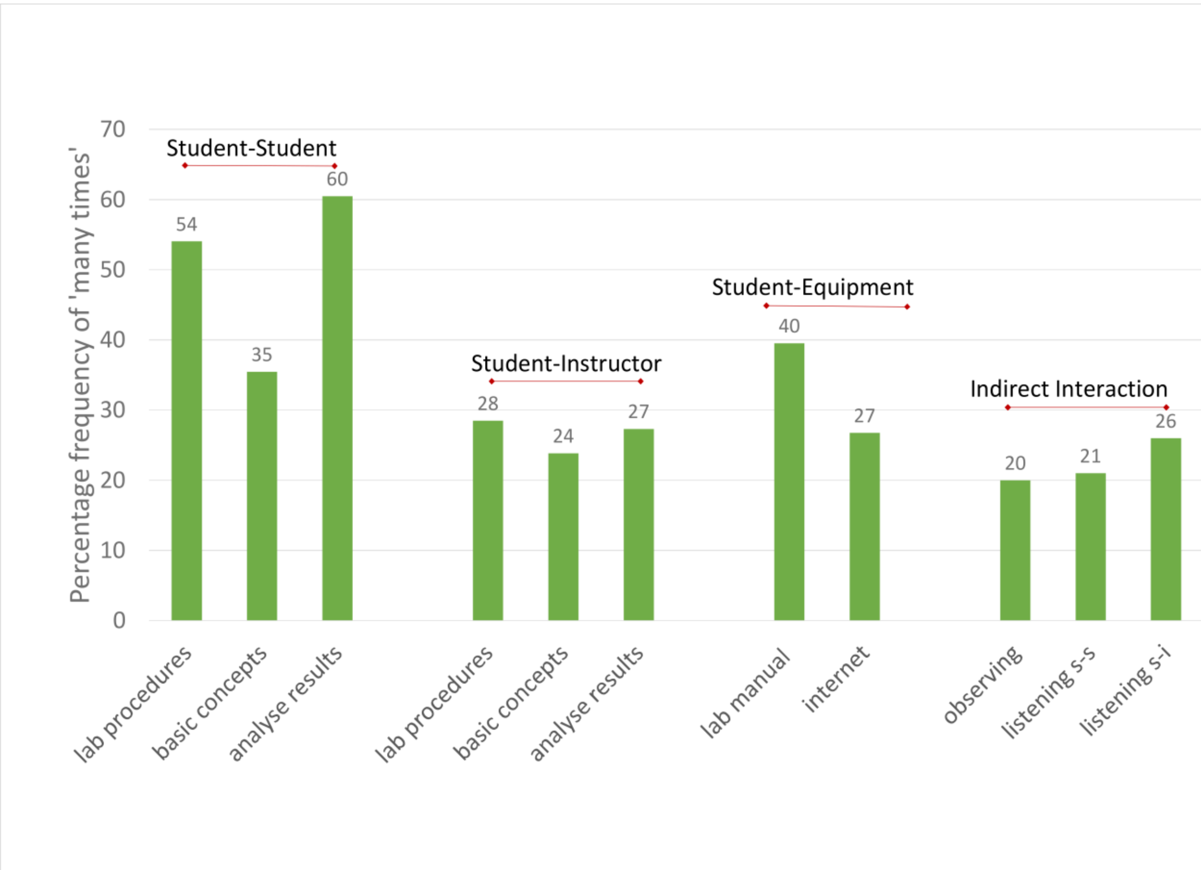

Figure 3 Relative frequency of the four types of interactions, sorted by task types, as reported to be 'many times' by students after undertaking the laboratory from seven sessions: data obtained from the post-lab survey ((total number of responses = 171)

* Note: the percentage of each item is not equal to 100% as we are only illustrating data of 'many times', not including data of 'never' and 'a few times'.

Results from laboratory observations

Both the pre-lab and post-lab survey results are based on students' feedback. To provide a more objective view, direct observation was also conducted. After combining all the seven laboratory observation results and dividing the number of occurrences of each item by the value of the overall occurrences (Figure 4), we observed that around one-third of student interactions were student-student talking about procedures. The second most frequent interaction was students asking instructors about basic procedures. Students also reflected on their results with each other or discussed them with instructors (clustered among 16% to 17%). Interactions not related to the topic of the experiment (both S-S and S-I) had a very low percentage. As indicated earlier, accurate documentation of indirect interactions is very hard in a laboratory class environment and consequently the data had low values. Because the observer focused on the whole class's verbal discourses, to make the observation unobtrusive, the observer would not move closer to listen carefully to the actual conversation content. This meant that even though some of the facial and/or physical features were not recorded as interactions, they were important clues for the observer to define the underlying interaction. The categorization of interactions also was dependent on the task content. Specifically, the observer recorded more procedural interactions when students were setting up apparatus and more results of analysis interactions were recorded when students were analysing their data. Thus, fewer occurrences relating to discipline concepts were recorded than for procedures and results analysis. Furthermore, the observer categorised unrelated topics only if the students were laughing loudly or talking about irrelevant topics loudly. Thus, there may be some quieter unrelated topics not being recorded.

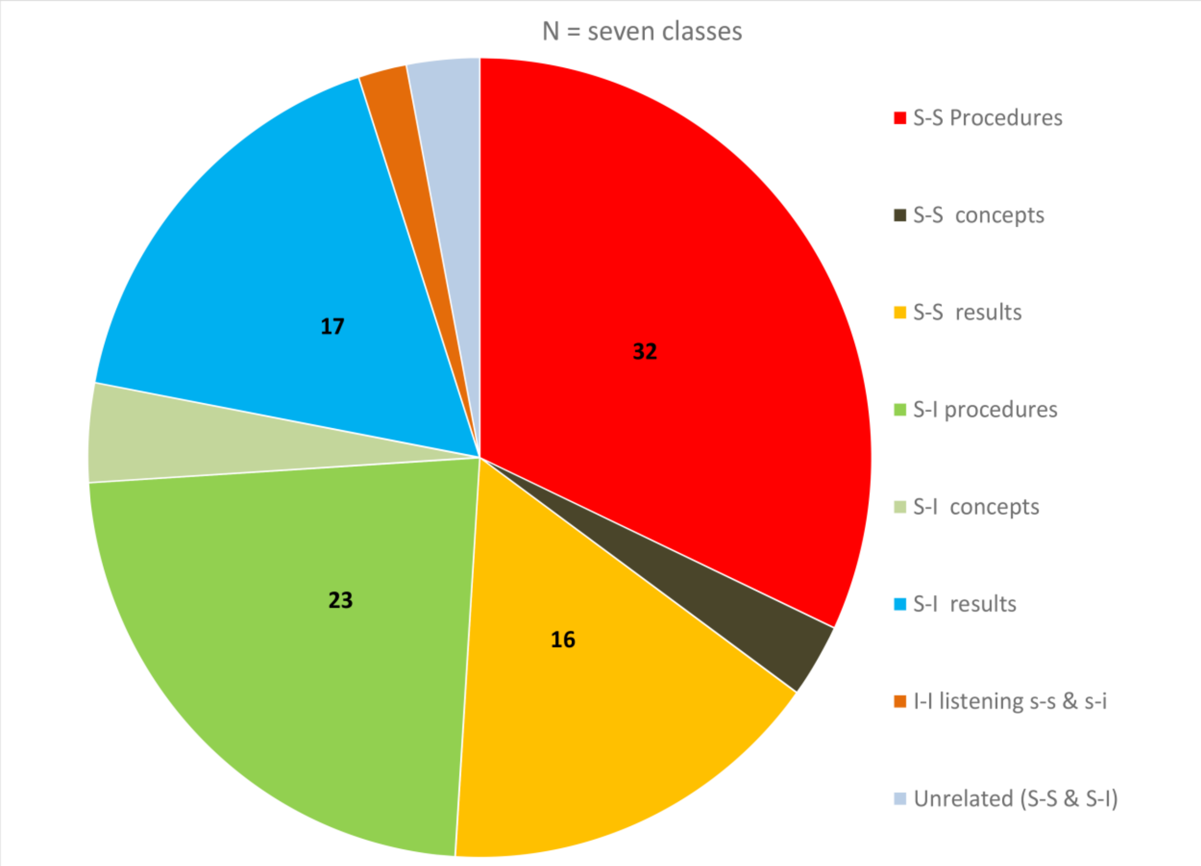

Figure 4 Observation results: proportions of each type of activity recorded during seven three-hour classes

The results from observations shown in figure 4 show good agreement with the students' self-reported results in figure 3 in that the S-S: procedures and S-S: results gave the highest proportions and frequency of interactions, respectively. Interactions with the laboratory manual were not recorded through the observations because these were so numerous that it proved impossible to separate them into individual occurrences. Nevertheless, the similarities between the results of self-reporting and observation suggesting students' self-reports can be used reliably as the main data collection technique in the present and other similar studies.

Relationship between Interactions and Student Achievement Levels

To address research question 3 - the relationship between interactions and student achievement levels, we first analysed the ranking responses of student categorised at the three levels of achievement. As shown in Figure 5, the highest achieving students anticipated that two-way interactions were more important, talking more with their peers or instructors. On the other hand, the lowest achieving students ranked one-way interactions (listening to the pre-lab demonstration, referring to laboratory manual, or surfing the internet) as more important.

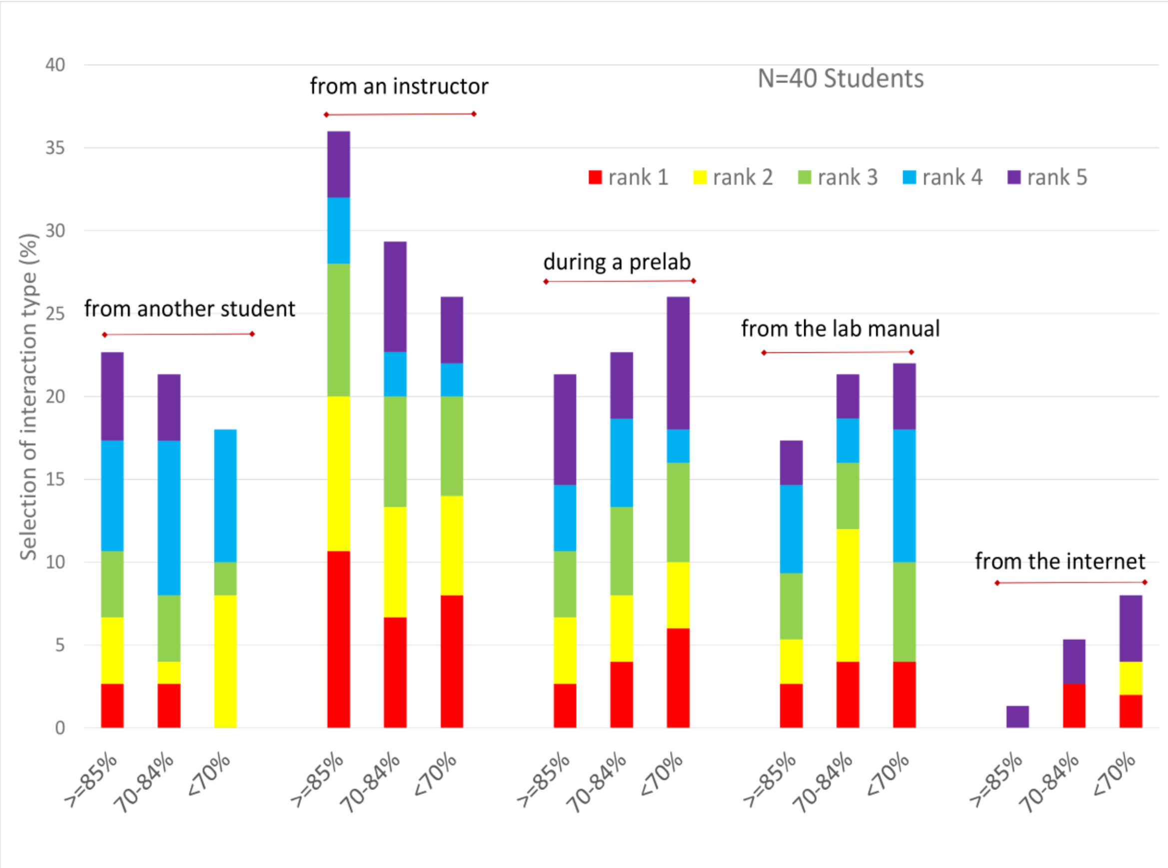

Figure 5 Student expectations of the importance of the potential interactions sorted by three student achievement levels before undertaking the laboratory: data obtained from the pre-lab survey (total number of selections = 40x5 = 200)

* Note: 1. Achievement levels are: >=85% equals the highest achieving level, 70% – 84% equals to the middle-level, and <70% equals to the lowest achieving level; 2. each column of >=85%, 70% – 84% and <70% sum to 100%.

Secondly, we analysed the responses from the post-lab survey according to the three levels of student laboratory achievement (Figure 6 & Figure 7). The results in Figure 6 show that each of the three groups of students reported that they interacted 'a few times' more often than 'never' or 'many'. However, the high-achieving students reported that they interact 'many times' more than students in the other two achievement levels.

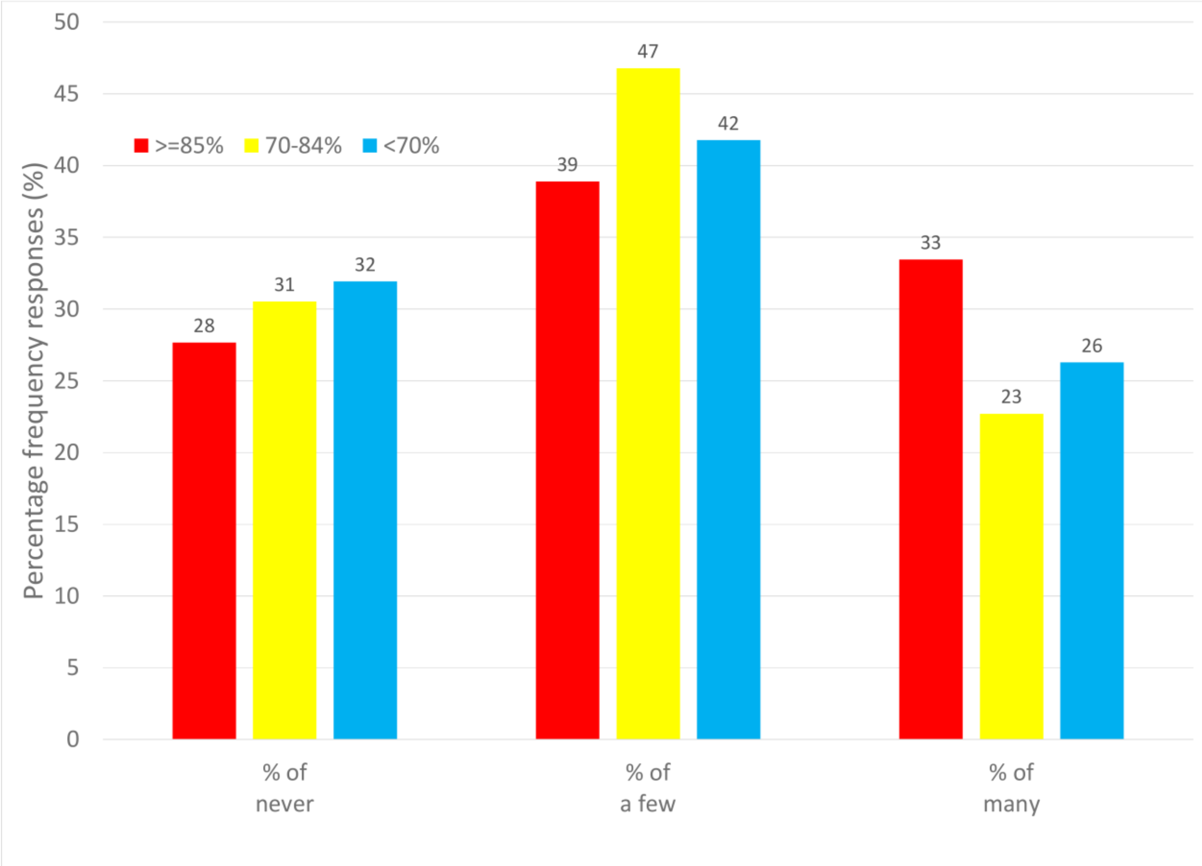

Figure 6 Relative percentage of the reported frequency of engagement level of laboratory interactions sorted by student achievement levels after undertaking the laboratory from seven sessions: data obtained from the pre-lab survey (total number of responses equal to 132)

<u>* Note: each column of >=85%, 70% – 84% and <70% sum to 100%</u>

We therefore made a more detailed analysis of the categories of ‘many times’; the results are shown in Figure 7. Compared with the low- and middle-achieving students, a relatively higher percentage of the highest achieving students reported that they interacted many times in all possible interactions.

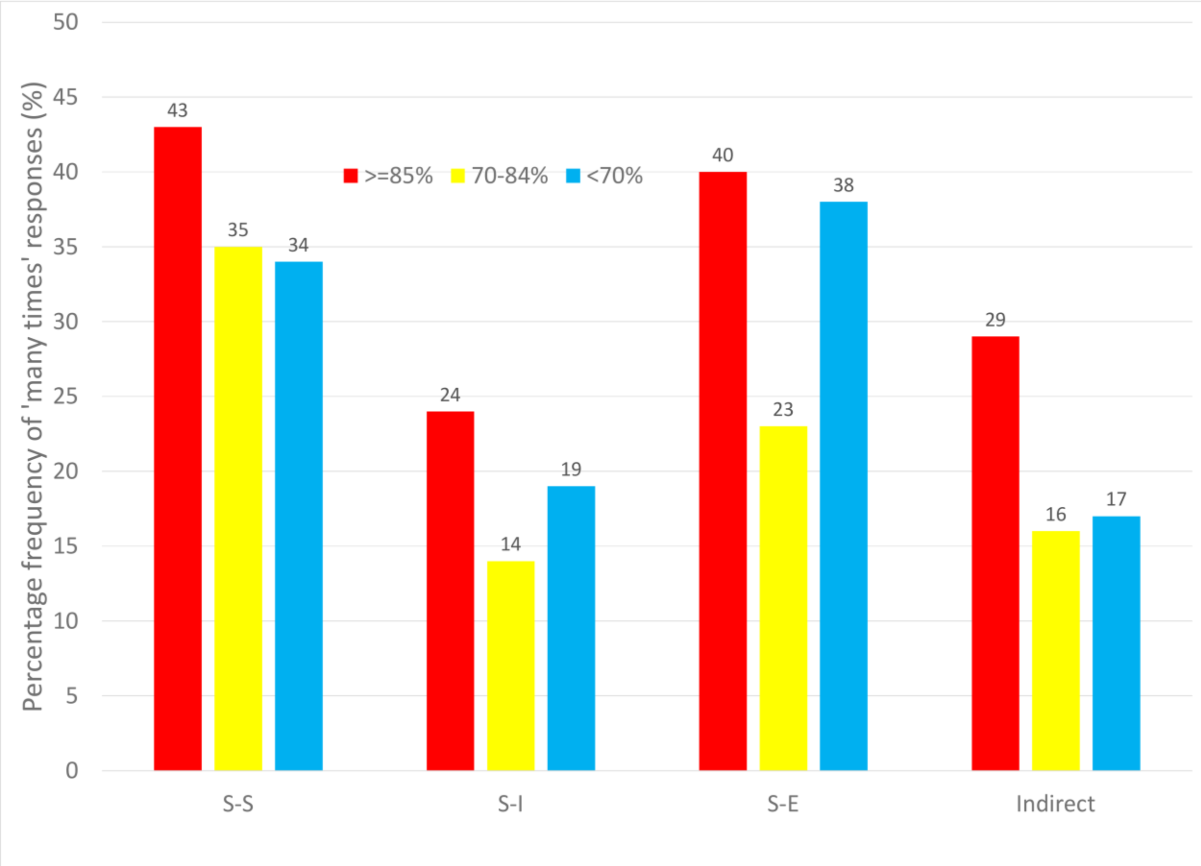

Figure 7 Distribution of interactions reported as 'many times' across the four types of interactions, sorted by the three student achievement levels: data obtained from the post-lab survey (total number of responses = 132)

<u>* Note: the percentage of each item is not equal to 100% as we are only illustrating data of 'many times', not including data of 'never' and 'a few times'.</u>

Discussion and Conclusions

This study was based on the analysis of one traditional undergraduate laboratory program of a first-year general chemistry course comprising 43 students who were studying Chemistry as part of their Biology degree. This research aims to provide recommendations for creating a more effective learning environment in chemistry laboratories. To achieve this aim, the research was guided by a theoretical framework developed from the Model of Educational Reconstruction (MER) that brought together the three elements of the learning environment, student perspectives, and achieving the course content.

The prelab survey addressed the first research question regarding students' perspectives of the relative importance of interactions. It was found that before they commenced the laboratory program, the students thought that asking the instructor about procedures could be the most important interactions. The reason for students asking instructors instead of their peers may be because their chemistry background was not strong and it was natural that people would seek assistance from a relatively authoritative person. Additionally, the first-year students were familiar with the high-school teacher-driven teaching style and tended to ask for help from instructors. This is in line with former findings that students acted more as initiators in S-I interactions than did the instructors (Velasco*, et al.*, 2016).

With regard to the frequency of interactions that actually occurred, the students reported that they talked with each other more often than with the instructors during the laboratory sessions. This observation is consistent with ideas of socio-constructivism that underpins the MER framework in that meaningful learning for students is situated in social collaboration and interactions with other people, especially with peers. Students' self-reports and observations both showed that interactions over procedures occurred most frequently, with interactions about results the second most frequent, while interactions about concepts were less often, which is in line with the former finding of (Kyle*, et al.*, 1979). Considering the fact that the students only had limited chemistry knowledge before this laboratory work and they were not given much freedom in these "cookbook style" laboratories, it is reasonable that more interactions were about following procedures. The instructor gave their marks at the end of each class, so the students had to hand in one complete laboratory notebook by the end of the class. This may explain why students thought that they spent more time on analysing results with their peers – to finish the task in time. Compared with these two kinds of goal-achieving interactions, interactions relating to discipline concepts occurred less often. The learners were possibly more focused on getting good scores than thinking about theory, or they might have been too busy in manipulating equipment than considering the basic concepts. Sandi-Urena and his group members (2011) showed that students who were constantly challenged to scrutinize and solve problems were using metacognitive and problem-solving skills. Thus, questions and tasks with groups should be carefully designed to provoke students' thinking, self-assessment and argument development. Indirect interactions have not been studied in detail by researchers for face-to-face laboratories. However, students reported that they had engaged in a large number of these interactions as could be expected because people generally repeat behaviours that are well received and avoid those that result in punishment (Bandura and Walters, 1977). Students learn how to set up or manipulate some glassware by observing other groups, as well as listening to other people's conversations. Students in laboratories may also avoid errors by learning from other groups' mistakes.

With regard to the third research question, students with different achievement levels had different views on the importance and frequency of interactions. The preference for interactions with other people (instructors or other students) by high-achieving students might show that they were more confident (Austin*, et al.*, 2018) and were not afraid of getting instant feedback. High achieving students implemented more interactions across all the four items (S-S, S-I, S-E, and I-I) compared with the other two groups. Other research has shown that high-achieving students were more self-regulated and the motivation to self-regulate was one of the driving factors in their academic achievement which is consistent with the MER (Mega*, et al.*, 2014; Austin*, et al.*, 2018). Thus they understood that learning from mistakes and correcting these mistakes were important in the learning process (Austin*, et al.*, 2018). That the lower achieving students preferred one-directional or interactions without instant feedback is consistent with research from Kousa et al. (2018), which showed that low-achieving students were likely to use internet, books or magazines to learn. Students' achievement level should be taken into consideration for curriculum designers (i.e., to prepare pre-lab activities, to improve the laboratory manual) and the instructors (i.e., to initiate some interactions with some students, assign groups according to student achievement levels) to meet each type of students' needs.

Limitations

A limitation of this project is the sample size being investigated, which comprised 43 students enrolled in one institution. Another limitation is that although it is assumed that people choose to act more frequently if they think something is important, more frequent interactions do not necessarily mean more meaningful engagement (Wagner, 1994). Whether there is a connection between high frequency of interaction between Student-Student and the anticipation of learning from instructors needs further analysis.

A further limitation is that the findings of observation are based on content analysis of verbal interactions at a whole-class level. The observer justified the features of the interactions by listening to students' conversations, their gestures and, for example, their watching of other groups. However, since there is a total of 20 students in the classroom, the observer sometimes could not unobtrusively walk closer to a sub-group to listen to its conversation.. The use of audio and video recordings in the observation process could be used to overcome this limitation. . It is also suggested that observations of a focused sub-group of students be conducted to provide insightful understanding of the students' behaviours.

Implications for Practice

Although we recognise foregoing limitations, we believe that the findings reported in this article can provide information about interactions occurring in chemistry laboratories and highlight features that may guide future laboratory observations and the development of strategies to promote effective engagement in laboratories.

Firstly, for S-S Interactions, our research has shown that most of the laboratory work happens between students so the importance of S-S interactions should not be overlooked in planning laboratory activities even though a high frequency of S-S interactions does not necessarily mean a high constructive learning process. S-S interactions could be cooperative, competitive or individualist, and among them, cooperative interactions have been identified as best to promote peer tutoring, information exchange and academic achievement (Johnson, 1981; Johnson and Johnson, 1987). These findings suggest that basic structured guidance may be provided to encourage productive interactions among students. Considering student achievement levels, high-level students tend to be the leader of a group because they have high self-efficacy and are likely to interact more. In this way, if different level students were in one group, the low achieving students may lose the opportunity to express their opinions. By contrast, if low achieving students were allocated separately, they may lose the chance to learn from more competent peers. More research is needed to identify how these factors influence students' laboratory learning.

Secondly, for S-I Interactions, the pre-lab survey illustrated that students thought that interacting with instructors could be more important for their learning. Various studies also showed that teaching assistants' (TAs) play important roles in the learning process (Herrington and Nakhleh, 2003; Rodriques and Bond-Robinson, 2006; Stang and Roll, 2014). Currently, most of the instructors are PhD students, most of whom do not have an educational research background and lack teaching experience. It is therefore necessary to provide suitable training programmes to help 'new' teachers be more confident and more effectively improves students' learning (Yang and Liu, 2004; Mocerino*, et al.*, 2015; Brouwer*, et al.*, 2017). We emphasize that in this training, not just the method of transferring knowledge, but also the way of communicating with students (i.e., how to talk with students to promote their thinking skills, to scaffold their learning instead of reducing their motivations, how to interact with different types of students) should be included.

Thirdly, for S-E Interactions, our study showed that the laboratory manual was considered to be a vital component of student learning. To address the problem that more time is spent on procedures or analysis of results than learning the major concepts of the discipline, the laboratory manual may be developed with a logical design and the learning objectives included to encourage students' concepts. We believe that a well-designed laboratory manual can influence students' learning especially for the lower achieving students, who assumed that the laboratory manual was more important than the high level achieving students before the laboratory. We also believe that asking for students' and the instructor's opinions about the laboratory manuals will help to improve them.

Fourthly, for I-I Interactions, our study showed that indirect or vicarious interactions can guide observers' behaviours in the learning process. This implies that indirect interactions should not be neglected in course design and class processes. Since most of the indirect interactions will happen between different groups in proximity, it might be beneficial to take indirect interactions into consideration when the instructors are assigning groups. Further research needs to be implemented to understand more about the influence of indirect interactions in chemistry laboratories.

Overall, to balance the frequency and length of these interactions with student engagement, learning experience and learning outcomes should be included in curriculum design, instructor training and laboratory class processes. In addition, students may need to be given some information about interactions during the orientation. The three elements in MER - students' perspectives, laboratory content and learning environment mutually influence each other and they should be taken into account when designing science laboratory learning.

Conflicts of interest

There are no conflicts to declare.

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