Understanding the nature of students' experience of pre-university practical work in physics

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Introductory practical work in university physics degrees is dominated by highly constrained and instructions-based tasks with limited value for developing students' scientific and critical thinking skills. One possible explanation for this may be the assumptions made about new students' prior experiences. Over the course of 5 years, approximately 800 first year physics students completed a simple survey of the *nature* of their prior experiences of physics practical work. An informative means of presenting the data and understanding their experiences as either passive or practical, or in terms of their freedom to make decisions, is developed. Most new undergraduate students have some experience of decision making in relation to physics practical work, which should be incorporated into course design. The data also indicates that different education systems provide different opportunities for decision making compared to other pre-university education systems, illustrating the need to align practical training at a local level.

I. INTRODUCTION

Despite the many documented benefits of open-ended practical work [1–6], the vast majority of introductory practical tasks in physics are highly constrained [7, 8]. Moreover, the name 'Experiment' is often misapplied [9–11]. Considerable student resistance to open-ended practical tasks has also been reported [12–14] which may hinder the introduction of genuine experimental experience at introductory levels, since there is high risk of conflict with students and poor student satisfaction, despite known issues and biases [15, 16].

One potential reason for reported resistance to open-ended practical work is a lack of alignment between students' prior experience and the presentation and structure of the tasks set. Misalignment may be more pronounced in introductory courses, not least because course designers lack knowledge about their students' needs and are therefore unable to meet their expectations [17] or identify interventions to manage them [18]. Not only may students' prior experience be assumed from formal qualifications, which are often dominated by written examinations [19], but contact with recent teachers who can provide an overview of a given cohort is clearly impractical. This can result in a gap between course organisers' assumptions about student readiness and required support and the students' actual preparedness [20, 21].

A simple survey collected data about the nature of students' prior experience of practical work and the analysis demonstrates several ways in which this can provide insight into both student preparedness and the pedagogical provision. Data collected over the course of five years is used to develop a means to understanding a student group's prior experience of practical work in physics in a way that can be used for both course transformation and contemporaneous adjustment. While the focus here is on prior experience, the questions are closely related to expectations, of both students and teachers, a topic that is rarely considered [17].

The majority of the discussion is in the context of University College London (UCL) where five years' worth of survey data is presented and discussed, indicating that students are prepared to make decisions about their method and even design their own investigations. The survey provides a tool for evaluating students' prior experiences of practical work in a way that can facilitate the introduction of appropriately advanced and independent practical work that builds constructively on students' prior experiences [21]. This can facilitate the alignment of educational provision to students, as seen in its application to the development work at Stockholm University (SU) [22], but it also promotes inclusive provision by ensuring that the necessary support is available for students whose prior ex-

perience may not leave them as 'well prepared' for the activities provided. If run every year, shifts in student experience can be tracked, and contemporaneous support adjusted even while the majority of written documentation remains static.

The rest of this paper is organised as follows. The survey and the raw results are introduced first. The survey items are then grouped thematically and the results for different groups of students are compared. Some thoughts about implications and usage are in the concluding section.

II. SURVEY OF PRIOR EXPERIENCE

In order to try to develop an improved understanding of first year students' experimental background and their preparation for undergraduate physics practical work, a survey of prior experience and expectations of physics practical work was created and introduced at UCL in autumn 2015. The data presented here is from 2015-2019 inclusive, during which time the anonymous survey was completed by approximately 800 students, including one cohort (40 students, 2018) at SU, where the survey was used to support changes to the practical work, replacing very precise instructions – 'set method' activities – with ones that required students to work out the method, and choose appropriate variable values, and also provided the opportunity for students to explore further, essentially developing their own experiment [22]. From 2015-2018, the UCL questionnaires were completed on paper, while in 2019, the questionnaire was electronic. The UCL questionnaires were all completed by students in their first session in the teaching laboratory. The SU group completed a paper survey during a compulsory course meeting at the start of the academic year, several weeks before starting practical work. Students were given a verbal briefing on the purpose of the questionnaire for improving course delivery and that all data was anonymous and completion of all parts was voluntary.

Prior experience was explored through a simple survey of five types of experience related to practical work that physics students starting at a British university may have experienced. Prior experience, particularly in relation to experimental decision making, was of especial interest at UCL where a key aspect of the first year physics training is the explicit focus on experimentation, principally through imperfect experimental set ups that provide opportunities for students to investigate anomalies [23]. In common with reports of resistance to inquiry [12–14], many students were seen to stick closely to the information provided which included most method details, and sometimes also suggested variable values, another example of 'set method' provision. This made finding out about prior experience of independence – and genuine experimentation – particularly relevant; in introducing the survey, experience indicated that this could take the two forms identified.

Survey description	Abbreviation
Designed, built and conducted own experiments	Own experiment
Conducted set experiments with own method	Own method
Conducted set experiments with prescribed method	Set method
Took data while teacher demonstrated experiments	Teacher demo
Analysed data from an experiment I did not conduct	Data analysis

TABLE I. The five aspects of experience as stated in the survey, and as referred to in the text and as used in figures. The survey question is: *"What is your experience of laboratory work related to Physics? (Tick all that apply)"*, and students selected 'lots', 'some' or 'none' for each aspect.

Five types of activity were identified as probable experience of students studying physics within the A-level system, and were listed in order of decreasing student involvement and control, as in Table I. The first three are closely related to levels in a simple characterisation of inquiry levels [7], and the two additional areas were included on the basis of experience of the A-level system. The statements were preceded by the question *"What is your experience of laboratory work related to Physics? (Tick all that apply)"*, and students ticked boxes of 'lots', 'some', 'none', for

the amount of experience they felt they had had of each aspect. This is similar to Likert-like (agree-disagree) scales commonly used for surveying students' attitudes [6, 24, 25], but is coarser grained, having just three options, one of which is unambiguously distinct from the other two.

This approach does not consider the frequency of practical work [26], and therefore neither relies on students recalling events from several months earlier, nor assumes that practical work is evenly distributed throughout students' studies. Intensive blocks of activities and more independent project work [21] are both incorporated. The simple scale also circumvents recall issues by allowing for impressions in relative terms – what might be called *perceived frequency* – as well as differentiating between different types of activity related to experimental science.

From its introduction in 2015, and up to and including 2018, the intake survey was completed on paper, and a few students provided partial information about their prior experience. The occasional student also either selected two (adjacent) of the three boxes, or carefully their tick on the line between two levels. In these cases, the experience level was always placed as 'some' since the students thought they had had some experience. In 2019, the survey was delivered online which enforced complete responses and that only one level was selected for each aspect.

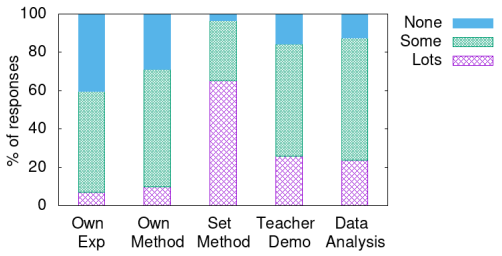

FIG. 1. (Colour online.) Summary of each aspect of prior experience: UCL, cumulative 2015-2019, as percentage of students who provided an answer for a given aspect. ('Exp' is abbreviation for 'experiment'.) The number of students who provided an answer for each aspect varies even within years, and is given in Table 2 of the supplementary material. Plots detailing the yearly and student-group variations are given in the supplementary material, Figure 1.

A. Cumulative summary

As seen in Figure 1, the most common type of practical experience was to perform a set 'experiment', according to instructions, followed by analysis of data from other sources and observing data collection. Since the survey question explicitly refers to the laboratory context, it is possible that the relative frequency of teacher-led demonstrations and data analysis are underestimated if students did not connect their experience and the statement. That most students reported a good amount of experience doing practical work themselves, and that many had also had considerable amounts of teacher-lead demonstrations, is consistent with earlier studies [21]. More distinctly, over 60% of students reported having some experience of designing and building their own experimental investigation, and an even larger fraction had had experience of making method-related decisions. However, more students reported no experience of decision making in relation to practical work than reported 'lots' of experience of data analysis and teacher-led demonstrations.

At this stage, incomplete responses are included, since each aspect is addressed separately. In the later sections, where aspects are combined, incomplete answers become problematic and are excluded. The number of responses and *complete* responses for each group and year are given in Tables 2 and 3 of the supplementary material respectively.

Even from this simplest presentation of the data, it is clear that pre-university training may not be preparing students well for independent practical work. On the other hand, many new undergraduate students have had some experience of independence in relation to their practical work, so highly instructed introductory practical work [7] may unnecessarily limit students' learning.

B. Student-level detail

The simple counting of reported experience (Figure 1) obscures any connections or correlations between different types of experience. In particular, it leaves open the question whether time spent on teacher-led demonstrations and data analysis corresponds to an absence of other types of experience. In others words: it might be expected that students who have little or no experience of decision making in their practical work, experienced more teacher demonstrations and data analysis, but this is not clear from Figure 1.

In Figure 2, each student from the group surveyed at SU in 2018, is represented by a vertical series of dots, coloured, shaped and offset according to the different types of experience. On the far left of each set, are students who responded with 'lots' to all types of experience; those who answered 'some' to building their own experiments and their own method occur in the centre; while those whose experience was more limited occur on the right. All students who answered the survey at SU provided complete responses to the five statements. When the survey was delivered on paper at UCL, a few number of incomplete responses were collected each year (supplementary materials, Tables 1 and 3). the SU group is unusual in that there is a higher degree of apparent correlation between experience types that is not present at UCL (supplementary materials, Figure 3). Overall, there is no means to inductively complete incomplete responses [27]. However, due to the small number of incomplete responses each year, the impact on the results and conclusions will be negligible, and partial responses are discarded in the following.

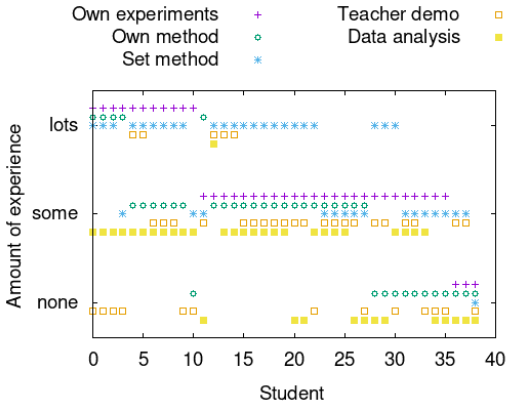

FIG. 2. (Colour online.) Individual responses for students at SU, 2018, ordered according to overall quantity of experience from most involved to least involved. The aspects are offset vertically for clarity. For a full set of plots, covering all years of the study, see Figure 2 of the supplementary material.

III. RESULTS: THE NATURE OF STUDENTS' PRIOR EXPERIENCE

The very action of ordering the students in some way, as done in the list of aspects and Figure 2, pre-supposes some sort of 'ranking' of the experiences, and ordering the experiences differently – organising the data differently – may lead to quite different interpretations. While plotting all students individually as in Figure 2 may be useful for a detailed understanding of the variability of a given student cohort, it is perhaps not so convenient for gaining an overview of or comparing different student groups.

It is also difficult to identify where a cohort's comfort zones may be, making it hard for teaching staff to align courses to students and ensure that additional support is ready for use. An easily interpretable presentation that can be analysed quickly and accurately is particularly relevant if information is collected at the start of an academic year for immediate application. Such a strategy and means of presenting the data is now developed.

A. Grouping of experiences

In reviewing the data in relation to the contexts in which it was collected and the purposes for which the survey was developed, it was realised that, to inform undergraduate practical training as the initial part of a research scientist's training, each type of experience can be classed in two ways (Table II). It may be 'active' or 'passive' depending

on whether or not the activity would involve students physically manipulating samples and equipment. It may also be 'controlled' or 'instructed' according to whether or not students are making decisions about the method and set up. This is approximate but intuitive: the purpose of introducing the survey was to obtain a broad overview, not require students to make a significant effort to remember their pre-university education.

Experience	Manipulation	Independence
Own experiment	active	controlled
Own method	active	controlled
Set method	active	instructed
Teacher demo	passive	instructed
Data analysis	passive	instructed

TABLE II. The five aspects of prior considered and their nature and independence classifications. The two short horizontal lines mark the different groupings; the 'set experiment; set method' type of experience is groups different to the other four types of experience that come as pairs.

The most ambiguous case is where a teacher demonstrates an 'experiment'. In these activities, students may contribute to the method, but it is likely that this will essentially be as pre-determined by the teacher. Equally, students may also handle the equipment, but it is likely that only a small subset of a class does so. When one considers the opportunities shared by an entire class, this aspect is passive and instructed.

Decision making in practical tasks can take many forms, for example deciding how to collect data or making changes to an experiment on the basis of observations [28], although this latter type of activity can rarely be completed in a single session. Despite the value of project-based inquiry activities [29, 30] with large elements of student control [7], the presence of genuinely open activities in both school and university introductory sciences [29, 30] is not universal, and a variety of excuses are even given for not requiring them [26]. At university level, the majority of laboratory or practical *courses*, as well as individual tasks [7] are highly structured, even when there is an accurate introduction to the nature of experiments [8].

The three point scale of the levels of experience ('lots', 'some', 'none') and the types of experience are qualitative descriptions and assigning them to a numerical scale must be done with care, although a degree of arbitrariness will remain. Between the limited number of distinct options, the unquantified gaps between the different levels and the descriptive experience types, correlative statistics are not appropriate [31].

From the point of view of potentially introducing practical work with significant decision making elements, the most important distinction is between 'some' and 'none', while the difference between 'lots' and 'some' plays a relatively minor role. However, one may also consider this stage as the identification of combinations of 'lots', 'some' and 'none' without considering which aspect this was associated with and assuming that 'some' of two different types of experience is roughly equivalent to 'lots' of one type and 'none' of the other type. This approach is meaningful for the process of gaining insight into the *nature* of students' prior experience with practical work, and aligning courses accordingly, and may also incorporate student confidence by reflecting *perceived* experience. This approach is similar to the handling of Likert-like agree-disagree scales so that strongly (dis)agreeing and slightly (dis)agreeing are considered as (dis)agreeing for analysis of trends [32]. Although here the 'lots', 'some', 'none', Likert-like part is already a three point scale. It is important to bear in mind that the purpose of the combination is to provide an improved understanding of where incoming students are and what they are used to, enabling better alignment of practical work to new students' needs [33, 34].

To enable comparison, the following procedure is used: the levels of experience are assigned numerical values: 'lots' = 2, 'some' = 1, 'none' = 0; the mean experience of each student in each of the four subdivisions is calculated (average practical, average passive, average control and average instructed), which preserves scaling; the number of students in each group with each pair of means (practi-

Own experiment	0	1	2	1
Own method	1	1	0	1
Set method	2	1	1	1
Teacher demo	1	2	1	2
Data analysis	2	1	1	0
Average practical	1.0	1.0	1.0	1.0
Average passive	1.5	1.5	1.0	1.0
Average control	0.5	1.0	1.0	1.0
Average instructed	1.67	1.33	1.0	1.0

TABLE III. Several examples of how combining the five-aspect raw data leads to contributions to different or similar groups in the two two-dimensional aspects.

cal/passive and control/instructed) is counted, and reported as a fraction of the total student group. In combining five sets of integer answers into a group of three and a group of two, and calculating the means, different combinations of experience can lead to the same mean, as demonstrated in Table III. This highlights the emphasis on the *type* of experience, particularly on decision making aspects, removing any tendency to rank different aspects.

It is now straightforward to apply the two grouping methods to the data. The manipulative experience is considered first, since this is the most obvious type, and can be investigated through knowledge tests [26]. Control and decision making, crucial for developing genuine scientific practice, are then considered in §III C. A summary of the data is discussed here, with additional student groups presented in the supplementary material.

B. Active and passive experience

Plotting the normalised occurrence (radius corresponds to percentage of total sample) of the data facilitates year to year and group to group comparison. From Figure 3, it is seen that new first year physics students generally report a good amount of prior experience of practical work (largest circles in centre and to the right), but passive work is also common. Extremes of passive experience were more common than of practical experience, and there is no indication of a significant trend

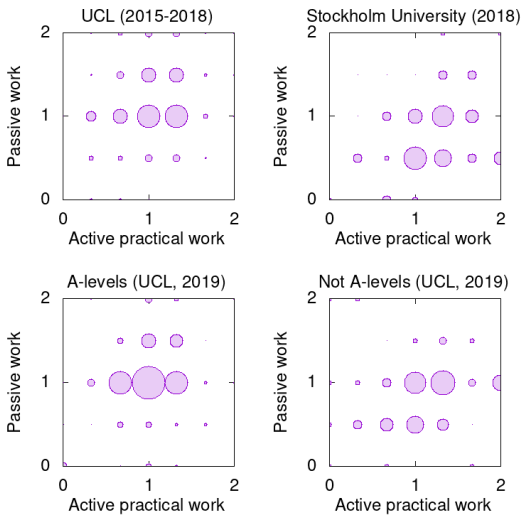

FIG. 3. (Colour online.) Average practical and passive experience for select groups. Similarities and differences between groups, for example the tendency towards passive experience at UCL, and the higher levels of active experience in non-A-level education systems, are visible. Detailed plots for all years and student groups are given in Fig. 3 of the supplementary material.

or correlation common to all groups.

The characteristics of the A-level system, in comparison to other education systems also seem to be distinct. The experiences of those who had taken A-levels are more firmly in the centre of the plot area, and with a slight tendency towards more passive (not hands-on) experience. This is in contrast with the experiences of students at SU (2018), and those at UCL (2019) who had not taken A-levels. These students not only reported more practical work (shift to the right), but also less passive work (larger circles lower in the plots). Moreover, for students who had not taken A-levels, more of one type of experience appears to correspond with more of the other type, thus more experience overall, a feature that is not present in the A-level data.

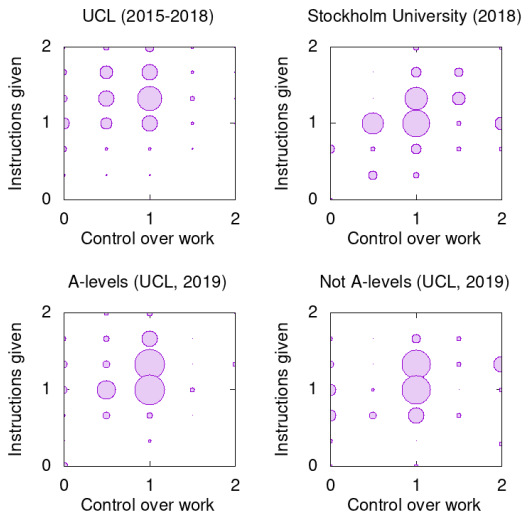

FIG. 4. (Colour online.) Average decision making experience (control/instructed) for select groups of students. The tendency towards higher levels of student control in non-A-level systems, are visible. Detailed plots are in Fig. 4 of the supplementary material.

C. Control and instructions

For the inclusion of inquiry activities – genuine experimentation – into introductory studies (first year), it becomes important to understand the other facet of the classification split outlined in Table II. That is how much experience students have had of making decisions about their practical work. Plots of the data organised in this way are shown in Fig. 4.

This reveals the dominance of 'set method' work shown in section II A. In particular, for students at UCL, many students had considerably more experience of instructed work and the extreme of control over work is virtually absent (bottom right hand quadrant of each plot almost empty, while the top left hand quadrant is filled). This is consistent with earlier work related to UK students' pre-university experiences of practical work in physics [21]. In contrast, at SU, there is a gap in the top left part of the plot (highly instructed experience), and a larger number of students reported lots of experience of experimental decision making. Non-A-level students at UCL in 2019 showed a similar trend to SU students, with the exception of a few students who reported no experimental decision making opportunities. This group is, however, comparatively small, and may originate from many different educational systems, so while the features are consistent with the non-A-level group at SU, differences in experience related to educational system would require further exploration with larger groups of students.

While the middle levels of experience dominated at SU, the fact that students' prior experience involved some experimental decision making was one of the key factors contributing to instructor confidence when introducing open-ended practical work [22]. In contrast, the more limited experience of first year students at UCL with making decisions about their practical work indicates that, where the dominant entry route is via the A-level system, more support and structuring is likely to be necessary.

IV. CONCLUSIONS

In the previous sections, self-reported student data of the type and quantity of pre-university practical experience in physics was presented and analysed. About 800 students completed a simple survey over five years, providing a large sample of students and covering the period of the A-level changes in England and Wales (first post-reform cohort in 2017). The five aspects of experience can be considered independently or classified in two ways: whether the student interacted directly with the equipment and measurement taking process or not; and whether or not the student was making decisions about their procedures and experimental set up. These facets can have implications for aligning introductory practical work at university, and the decision making aspect may be particularly relevant for introducing more open-ended work which can meet student resistance [12–14]. These groupings lead to two-dimensional plots that provide an overview of a cohort's prior experience.

From Figures 3 and 4, we see that most first year physics students have some experience of both practical work and decision making in re-

lation to it. Given that the majority of first year undergraduate physics practical tasks are highly instructed [7, 8], it is clear that these may not be well aligned to students' prior experience and it should be possible to incorporate considerable elements of student control and decision making [21, 22]. Given the resistance to more open-ended work [12–14], this would need to be supported by an introduction to the experimental process and scientific practice [35]. The survey and analysis method presented here can be used to design university practical training that builds constructively on students' prior experiences. Student choice between 'some' and 'lots' may reflect self-efficacy or confidence, and an important additional aspect to consider in course design is that students from less privileged backgrounds may have had fewer opportunities and lack confidence in their abilities [36–39].

While it might be tempting to investigate correlations within and between groups on the basis of the raw data, the unquantifiable (ordinal) data makes such an exercise meaningless [31]. Variations between and within groups are easily seen in the visual representation developed here where the axes retain meaning, information that is lost if a numerical measure of similarity is used (discussed further in the Supplementary Material). The analysis presented here should be understood as a tool that can be used to proactively adjust practical work to students' needs [34]. However, the survey in the form presented here was developed for its immediate context, with the assumption that the statements developed would be interpreted as anticipated by the students. It is strongly recommended that the survey is reviewed and adjusted with some who can be taken as representative of the student group of interest before large scale implementation to improve the reliability of the results obtained. A number of aspects to consider, and possible ways of achieving good understanding the perspectives of – and any mismatches between – survey setter and survey takers, are summarised in Section 5 of the Supplementary Material.

The use of the survey as part of the development work at SU demonstrates its relevance and usefulness by applying it to a situation with a very different pre-university educational system, and highlights its utility for course design and alignment [22]. It also indicates that there may indeed be systematic differences between A-level and non-A-level education systems; further use of the survey in diverse contexts with a dominant intake route would be required to fully explore this. The comparison (non-A-level) group sizes are small, but they provide a preliminary indication that the A-level system may provide fewer opportunities for student decision-making than other systems, emphasising the need for understanding the local situation for developing practical work aligned to students' prior experiences. Understanding what students are prepared for, particularly in light of curriculum changes and increasingly diverse student backgrounds and aspirations, is important for high-quality, effective education and inclusive practice.

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