Gender differences in conceptual understanding of Newtonian mechanics: a UK cross-institution comparison

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Abstract

We present the results of a combined study from three UK universities where we investigate the existence and persistence of a performance gender gap in conceptual understanding of Newtonian mechanics. Using the Force Concept Inventory, we find that students at all three universities exhibit a statistically significant gender gap, with males outperforming females. This gap is narrowed but not eliminated after instruction, using a variety of instructional approaches. Furthermore, we find that before instruction the quartile with the lowest performance on the diagnostic instrument comprises a disproportionately high fraction (\textasciitilde50\%) of the total female cohort. The majority of these students remain in the lowest-performing quartile post-instruction. Analysis of responses to individual items shows that male students outperform female students on practically all items on the instrument. Comparing the performance of the same group of students on end-of-course examinations, we find no statistically significant gender gaps.

1. Introduction

There are ongoing concerns about female participation and performance in academic physics. Here we examine the gender differences in performance in Newtonian mechanics within introductory physics courses at three UK universities, using the Force Concept Inventory

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Developed by Hestenes and co-workers at Arizona State in the early 1990s, the FCI has become the gold standard diagnostic test of conceptual understanding in physics [1]. Following Hake’s landmark paper in 1998 [2], in which the efficacy of different instructional methodologies was evaluated using this instrument with a sample of nearly 6000 students, it has become widely accepted and used within the discipline community. It has also served as the benchmark for the subsequent creation of a wide variety of instruments and inventories for use in science teaching and learning, currently numbering over 50 [3].

Several studies from US institutions have previously investigated the performance gender gap in introductory physics courses using the FCI instrument. (We use gender in this context as equivalent to sex; we are aware that this can rightfully attract criticism [4].) The standard methodology of implementation is to assess students with the instrument prior to instruction and then again after instruction (the so-called ‘pre- and post-test’ methodology). Lorenzo et al [5] presented extensive data from Harvard students undertaking an introductory calculus based course between 1990 and 1997. Their data indicate the presence of a statistically-significant gender gap on the pre-instruction tests, expressed as difference in the mean score by male students and the mean score of female students, with male students consistently outperforming female students. Furthermore, they contend that certain instructional methodologies are more effective at reducing (or eliminating) the performance gender gap, specifically the interactive engagement style of lecture instruction emphasizing peer instruction and discussion that Eric Mazur developed in the late 1990s in response to students’ initial performance on the FCI at Harvard. In a replication study at the University of Colorado, Pollock et al [6, 7] found that use of interactive engagement instructional methodologies is not necessarily sufficient to close or eliminate the performance gender gap on the FCI, citing examples where, despite overall improvements in performance between pre- and post-instruction tests, the gap was found to widen. They suggest there are additional effects due to differences in student preparation and background, as well variability in instructors. Docktor and Heller [8] have presented an analysis of data collected from 40 separate classes, 5500 students and 22 different instructors. They too confirm the presence of a significant gender gap pre-instruction, which persists post-instruction overall, though the individual (per class) changes in the performance gender gap span a broad range from +7% (gap widens) to −6% (gap narrows).

We are motivated to re-examine this in the context of UK physics undergraduates, in part because of the lack of clear consensus in the literature, but moreover because both the style of university education and the preparation prior to coming to university are very different from those in the USA. Additionally, many of the studies referred to above relate to courses delivered to non-majors in physics, sometimes with atypical gender profiles (for example, the Harvard courses referred to above have a male:female student ratio of less than 2, whereas undergraduate courses in the UK typically have ratios closer to 4). Our previous studies, using a widely-accepted instrument to survey students’ attitudes and beliefs about physics, have indicated there can be significant differences in the response profiles of US and UK students undertaking introductory physics courses [9], and this is worthy of further investigation with respect to gender and performance on the FCI.

We apply our investigation to a typical UK cohort of students, in which female students are under-represented. Over the past 10 years of A-level examinations (the most common school leaving examination in England, Wales and Northern Ireland) we have seen a dramatic rise in the overall uptake of mathematics, a slight decline followed by a slight rise in physics, and a minimal rise in chemistry. Over the same time period the proportion of females taking physics has dropped marginally, from 23 to 21%, and is much lower than comparable figures for mathematics (constant at about 40%) and chemistry (a slight decrease from 51 to 47%) [10]. There is at least some evidence that female students taking a physics A-level exam are
more able than their male colleagues, but at the same time their motivation for studying physics may be much more geared towards the medical sciences [11].

At tertiary level, the Institute of Physics (IOP) has collected data that show that the proportion of females entering first year undergraduate physics in the UK has remained between 18–20% for the last 15 years [12]. Female participation is, therefore, a key issue. Allied to that is the issue of retention as students progress through their education. The relatively poor progression of females to the most advanced courses in physics has been referred to as a ‘leaky pipeline’ [13], with proportionately more female students leaving programmes of study at early stages. It is a contributing factor to the fact that, based on US data, physics has one of the lowest proportion of female PhD graduates of all disciplines [14].

This study presents results from pre- and post-instruction testing using the FCI at three different UK universities: Edinburgh, Hull and Manchester. Our study has the following aims:

(i) to evaluate the existence and possible persistence of a performance gender gap in introductory (first year of study) physics courses;
(ii) to evaluate individual test items that display significant differences in performance of male / female students.

This paper is organized as follows. In the next section we detail the different course contexts at the three institutions and the methodology used to obtain and analyse test data. We then present results from the three universities and in the final section discuss both these results and their implications.

2. Methodology

2.1. UK education context

We briefly summarize the educational background from which the vast majority of our undergraduate intake is drawn for readers not familiar with the UK system. There are three main sets of qualifications for our intakes.

- **A-levels**, taken by the majority of students from England, Wales and Northern Ireland, and some from Scotland. The final two A-level years follow on from six years of primary schooling and five years at secondary school where a broad set of subjects is studied. Students generally take a minimum of three subjects for these final two years before going to university. The results for each subject are reported as letter grades (highest grade A*, other pass grades A–E, and U=‘unclassified’ as a failing grade) and are obtained from a combination of the results from a set of modular exams. Within this system there are various syllabuses for both mathematics and physics, and physics itself is taught in a manner which largely avoids the use of calculus. Students are exposed to more of the mathematical rigour of physics if they choose so-called ‘mechanics modules’ (elective modules on the mathematics of Newtonian mechanics) as part of their mathematics A-level.

- **Scottish Higher qualifications**, taken by most Scottish students, since Scotland has a separate education system. Entry to universities in Scotland is based on performance in these qualifications, taken at the end of year five of secondary level. Typically five subjects are studied to Higher level. Most students stay on for a sixth year at secondary level, taking (usually) three subjects at Advanced Higher level.

- **Finally**, a growing fraction of our students enter with the UK International Baccalaureate. It consists of three specific core elements, and study of six elective subjects, three of which are at higher level.
The typical age of an incoming student to undergraduate physics programmes in the UK is 18 or 19 (occasionally 17 from Scotland). The school system in the UK is funded through a variety of sources, where the most important difference with the rest of Europe is the larger number of students studying at privately funded schools. First year students at the three universities in this study (two from England, one from Scotland) therefore comprise a diverse group in terms of their prior academic background and ability.

2.2. Institutional contexts and course details

All three institutions have been utilizing the FCI (or a close variant thereof) as an assessment instrument within their introductory physics courses for a number of years. We all had slight differences in our approach to the FCI, but we have aligned our processes in the 2011–12 academic year, on which this work is based. Due to a substantial increase in tuition fees in England for 2012, this was also a year when entry qualifications were higher than in recent previous years.

All three universities require both physics and maths school-leaving qualifications for students wanting to study physics courses. There are, naturally, differences between the cohorts and courses at the three universities, which are detailed below.

2.2.1. Edinburgh. The School of Physics and Astronomy at the University of Edinburgh has an annual undergraduate intake onto the physics degree programme of about 120 students, of whom 21–25% are female. Approximately 60% of students enter the University with Scottish school-leaving qualifications (Highers or Advanced Highers), 30% have taken A-level exams, and the remainder have taken other qualifications such as the International Baccalaureate.

The Scottish Bachelor’s degree has a normal duration of four years (one year longer than in the rest of the UK), with a first year that is slightly broader than that in England. The first year class studied here comprises students for whom physics is a mandatory requirement for their degree programme (mainly students on physics degrees) and those who are taking it as an outside subject or an elective. In recent years, each of these constituents comprised about half the class, thus the total class size ranges from 200 to 300 students each year.

The 11-week course has for many years been a focal point for curriculum innovation within the School, and details of the instructional design [15], the role of studio-based workshop classes [16], student generated assessment content [17] and the move to ‘invert’ the traditional lecture environment [18] have been reported elsewhere. In the 2011–12 presentation of the course, for which we report data here, the most significant change was the inclusion of the latter two interventions (student-generated assessment content and the ‘inverted’ classroom approach) in the standard presentation of the course.

2.2.2. Hull. At the University of Hull, the first year physics intake has doubled in the last four years and stood at 70 students in 2011/12, 10% of whom were female. The vast majority of students enter the 3-year BSc programme with A-level qualifications.

Classical mechanics is taught through a modelling curriculum [19]. As is common in modelling instruction, we base student-generated models on group discussion, but due to institutional constraints the course was delivered in a conventional lecture theatre, which meant that, at best, the discussion was limited to neighbouring pairs of students. The course is taught over a ten-week period in the first semester of the first year, with each lecture mixing elements of formal instruction, interactive engagement and discussion between neighbours. The formal instruction is based on a structured approach to the use of multiple representations in constructing models, with the role of representations in evaluating, describing, analysing
Table 1. FCI implementation details at participating institutions.

| University       | FCI used since | Delivery mechanism | Time limit | Timing pre-/post-final mark (%) |
|------------------|----------------|--------------------|------------|---------------------------------|
| Edinburgh        | 2006\textsuperscript{a} | Online             | 90 min     | Weeks 1 / 8                     | 3                      |
| Hull             | 2008\textsuperscript{b} | Paper   none       |            | Weeks 0 / 10                     | 0                      |
| Manchester       | 2008           | Paper             60 min | Weeks 0 / 6 | 0                              |

\textsuperscript{a} Between 2006 and 2010 a variant of the FCI was used with additional questions.  
\textsuperscript{b} Matched pre- and post-data were collected for the first time in 2011.

and solving problems being emphasized. Interactive engagement and peer discussion are used primarily to provide students with opportunities to use multiple representations for themselves. Details of the method and the conceptual gains have been described elsewhere [20].

2.2.3. Manchester. The first year undergraduate intake to the School of Physics and Astronomy at the University of Manchester comprises between 230 and 290 students per year, of which approximately 20% are females. Nearly all the students are registered on either a 4 year MPhys or a 3 year BSc degree in physics, some with a subsidiary subject such as astrophysics. A small fraction of the students are registered on a joint mathematics and physics degree programme.

The vast majority of entrants possess A-level qualifications, however the students’ prior experience of Newtonian mechanics varies considerably depending on their choices of optional modules within their mathematics A level and, if they chose to do take it, further mathematics A level. The median number of mechanics modules taken is 2, but some students do not study any of these optional mechanics modules at A level whereas others may have studied up to four or five (depending on which of the five A-level examination board papers they have sat).

All students take a Newtonian mechanics course in their first semester at university. The 11-week course has been taught in a non-traditional manner for several years, using interactive techniques such as an electronic voting system (‘clickers’), peer instruction [21] and Just-in-Time Teaching [22]. A comprehensive suite of e-learning material is used to support the students’ learning and weekly online assignments encourage students to consolidate their understanding as the course progresses. These teaching techniques have had a positive impact compared with the previous traditional approach, both in terms of student satisfaction and examination performance [23, 24].

2.3. Implementation of the FCI

A summary of the implementation procedures employed at the three institutions is presented in table 1. In the case of Edinburgh, where the FCI score contributed to approximately 3% to the course mark, it was the better of a student’s two attempts that counted.

2.4. Statistical tests

Since our data are represented in two two-way contingency tables (one dimension is male or female, the other their score on one of the FCI tests), the best approach to see whether the differences between males and female students are significant is the Pearson $\chi^2$ test of association. This test is based on a test statistic that measures the divergence of the observed data from the values that would be expected under the null hypothesis of no association. This
requires calculation of the expected values based on the data; the expected value for each cell $(i, j)$ in a two-way table $d_{ij}$ is equal to

$$
\tilde{d}_{ij} = \left( \sum_i d_{i\cdot} \right) \left( \sum_j d_{i\cdot} \right) / n,
$$

where $n$ is the total number of observations in the table. The statistic is defined as

$$
\chi^2 = \sum_{ij} \frac{(d_{ij} - \bar{d}_{ij})^2}{\bar{d}_{ij}}.
$$

This is distributed as a $\chi^2$-distribution with $(N_{\text{column}} - 1)(N_{\text{row}} - 1)$ degrees of freedom, and we can test whether the observed value for the statistic is significant by looking at the $P$ value for the $\chi^2$ distribution.

The alternative of approximating the two sets of mark distribution as continuous is also attractive; the disadvantage of that approach is that the data are not normally distributed, mainly due to the fact that scores on the post-instruction test are close to the maximum, and thus fluctuations above the mean have only a limited range. Thus the standard $t$-test for the equality of the means does not apply. We have applied the Mann–Whitney U test to test the difference between the distributions of the independent data sets.

3. Results

3.1. Quantitative data analysis

The FCI was administered to each cohort before and after relevant instruction. In the presentation of results that follows, only matched pairs of data (i.e. data for students who had taken both the pre- and post-instruction tests) are included. Thus the sample size for each institution is lower than total class size.

For the members of each cohort undertaking both a pre- and post-instruction test, we calculate the pre- and post-instruction average percentage scores $\langle x \rangle_{\text{pre}}$ and $\langle x \rangle_{\text{post}}$. This allows us to calculate a cohort-averaged normalized gain, $\langle g \rangle$ defined as

$$
\langle g \rangle = \frac{\langle x \rangle_{\text{post}} - \langle x \rangle_{\text{pre}}}{100 - \langle x \rangle_{\text{pre}}}.
$$

This normalized gain is often considered as a measure of instructional effectiveness, representing the fractional improvement in understanding, as first described in Hake’s study [2]. The normalized gain can be calculated for the entire cohort, or just the male or female sub-cohorts, using the appropriate mean FCI scores.

For the analysis of the male and female sub-cohorts, we can define a performance gender gap, $G$, as the difference between male and female mean scores, such that

$$
G_i = \langle x \rangle_i^{\text{male}} - \langle x \rangle_i^{\text{female}}
$$

where the subscript $i$ denotes pre- or post-instruction, and the convention we have adopted is that positive gaps imply male students outperforming female and vice versa. We can define a change in this gap, $\Delta G$, as the difference between values of $G$ determined for post- and pre-instruction, such that

$$
\Delta G = G_{\text{post}} - G_{\text{pre}}
$$

where the convention here is that a positive value of $\Delta G$ denotes a gap that widens as a result of instruction, and negative $\Delta G$ denotes a gap that narrows.
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Figure 1. Gender gap, \( G_i \), defined as the difference between the mean male cohort score and the mean female cohort score on the FCI, for pre-instruction (white) and post-instruction (hatched) testing.

Table 2. Cohort performance on the FCI. Values in parentheses are the standard error of the mean; see text for definition of other quantities.

| Institution | Group       | N  | Assessment | \( \langle x \rangle \) | \( \langle g \rangle \) | \( G \) | \( p \)  | \( \Delta G \) |
|-------------|-------------|----|------------|-----------------|--------------------|--------|-------|----------|
| Edinburgh   | Whole class | 161| Pre        | 64.4 (1.7)      |                    |        |       |          |
|             |             |    | Post       | 83.9 (1.2)      | 0.55               |        |       |          |
| Hull        | Whole class | 46 | Pre        | 59.1 (2.7)      |                    |        |       |          |
|             |             |    | Post       | 75.9 (2.4)      | 0.41               |        |       |          |
| Manchester  | Whole class | 258| Pre        | 76.4 (1.0)      |                    |        |       |          |
|             |             |    | Post       | 87.6 (0.7)      | 0.48               |        |       |          |
| Edinburgh   | Male        | 116| Pre        | 67.4 (1.9)      |                    |        |       |          |
|             | Female      | 45 | Pre        | 56.8 (3.2)      | 10.6               | 0.005  |       |          |
|             |             |    | Post       | 86.0 (1.3)      | 0.57               |        |       |          |
| Hull        | Male        | 40 | Pre        | 78.3 (2.7)      |                    |        |       |          |
|             | Female      | 6  | Pre        | 42.8 (6.1)      | 18.7               | <0.001 |       |          |
|             |             |    | Post       | 77.3 (2.6)      | 0.41               |        |       |          |
|             | Female      | 6  | Post       | 67.2 (4.6)      | 0.43               | 10.1   | <0.001| -8.6     |
| Manchester  | Male        | 198| Pre        | 79.4 (1.0)      |                    |        |       |          |
|             | Female      | 60 | Pre        | 66.3 (2.4)      | 13.1               | 0.015  |       |          |
|             |             |    | Post       | 89.4 (0.7)      | 0.49               |        |       |          |
|             | Female      | 60 | Post       | 81.9 (2.0)      | 0.46               | 7.5    | 0.050 | -5.6     |

Table 2 presents values for these quantities for all three institutions. Cohorts from all three institutions show substantial learning gains on the FCI, comparable with those seen on 'reformed' courses in studies reported in the literature [2], providing evidence for effective (even though they are all rather different) instructional methodologies. However, all three institutions show a consistent performance gender gap (\( G \) positive) on the basis of pre-instruction test results, ranging from +10% to +19%. Furthermore, this gap persists on the post-instruction assessment and is statistically significant (\( p < 0.05 \)), but is reduced in all three cases. Figure 1 illustrates this, presenting the male and female sub-cohort data for pre- and post-instruction tests in graphical form.

Table 2 illustrates that on the basis of the pre-instruction test, female students start the courses with lower FCI attainment. It is instructive to investigate the distribution of these
students across the cohort and chart their later outcomes on the post-instruction test. To do this, we split the cohort on the basis of pre-instruction test performance into quartiles (of approximately equal size) at each institution. We then further separate each quartile into male and female subgroups. The performance on the post-instruction test of these gender-split quartile groups for each institution is presented on figure 2.

For the data from Hull, there are no female students in the top two quartiles and the rather small sample sizes (particularly of female students) means it is not sensible to try and draw too many conclusions from the data in figure 2(b). For the larger sample sizes of the Manchester and Edinburgh cohorts, there was no statistically significant difference in post-instruction test scores of the male and female cohorts within each quartile group.

However, we do note that in case of the lowest quartile for all three institutions, the mean post-instruction test score for this quartile barely reaches the pre-instruction whole-cohort average for that institution. In other words, on average, students in the lowest quartile pre-instruction show the lowest normalized gains post instruction. Another way to analyse the data is to consider the ‘churn’ between students in the lowest ability quartile on both the pre-instruction and post-instruction tests. Considering the Edinburgh data, we find that approximately 70% of students initially in the lowest quartile are also found in the lowest quartile on the post-instruction test, with all of the remainder elevated to just the third quartile. For Manchester almost 60% of those students initially in the lowest quartile on the basis of pre-instruction FCI scores remain there.

Further insight into the consequences of these results can be gained if we consider the relative proportions of male and female students in each of the four pre-instruction test quartiles: so as not to overcrowd figure 2, this is presented separately in table 3. This illustrates that the fraction of male students in each of the four quartiles is approximately equal, and furthermore this is consistent for the male student cohorts from all three institutions. In other words, prior to instruction, male students are distributed approximately evenly throughout the ability range as determined by the FCI. In contrast, there is a starkly different picture for female students. Across all three institutions, approximately half the female students in each of the institutions are in the lowest ability quartile prior to instruction (final column in table 3). Taken together, figure 2 and table 3 present a worrying picture, for both the starting point and outcome for female students. Approximately half start in the lowest quartile, the majority remain there, and for these students, figure 2 shows that their post-instruction test performance remains, on average, the lowest of all eight sub-cohorts for the larger data sets from Edinburgh and Manchester.

It may be tempting to suggest that this is due to these students simply being weaker at the point of entry. We find no evidence for this in their prior qualifications, though it is difficult to obtain good, discriminating, quantitative data since most entrants arrive with very similar

Table 3. Fraction of male and female students in each quartile group of pre-instruction FCI scores. $N_{tot}/M/F$ represents the number of students in total, those who are male and those who are female, respectively. $f_{M/F}$ gives the fraction of male or female students, respectively, who are in each of the four quartile groups Q1 (highest) to Q4 (lowest) expressed as a fraction of the total number of male or female students in the cohort.

| Institution | $N_{tot}$ | $N_M$ | $N_F$ | $f_M$ | $f_F$ | $f_M$ | $f_F$ | $f_M$ | $f_F$ | $f_M$ | $f_F$ |
|-------------|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Edinburgh   | 161      | 116   | 45    | 0.30  | 0.13  | 0.24  | 0.20  | 0.22  | 0.22  | 0.23  | 0.44  |
| Hull        | 46       | 40    | 6     | 0.20  | 0.00  | 0.33  | 0.00  | 0.25  | 0.50  | 0.23  | 0.50  |
| Manchester  | 258      | 198   | 60    | 0.21  | 0.03  | 0.30  | 0.20  | 0.29  | 0.27  | 0.21  | 0.50  |
school leaving qualifications, frequently at or close to the highest grade bands. Furthermore, we have far from complete data on the number of mechanics modules taken by these students.
during their final secondary school study of physics and maths, so even comparing students with the same grades may not reflect their prior exposure to Newtonian mechanics. By looking across a wider population of UK students, rather than simply the fraction that attend our institutions, there is clear evidence that female students outperform male students in school-leaving examinations, including physics [10]. In the US, the situation seems to be slightly different. Sadler et al., considering the impact of high school and other affective experiences [25] have reported that the overall background of female students entering college physics was stronger in most subjects, but not in physics. Nevertheless, they conclude that the stronger academic background of females entering college physics did not appear to help them perform better than males; in fact, they performed worse than their male counterparts with the same academic backgrounds.

3.2. Item analysis

Given these differences, it is reasonable to question whether they arise from a greater fraction of male students getting certain questions (items) on the FCI assessment correct, or whether the origin is a consistent outperformance across the entire test.

In figure 3, we plot the fraction of male students getting an individual item correct against the corresponding fraction of female students who do likewise, for each of the 30 items on the FCI instrument. Even though we already know we have a performance gender gap, and thus are not expecting the line of unit slope to represent a line of best fit to the data, the data confirm that a larger fraction of male students get a given item correct compared to their female counterparts, for almost every item on the instrument (i.e. the majority of points lie above the line of unit slope, with the exception of only a small number of items for both pre- and post-instruction assessments).

The largest gender differences tend to occur for items that are generally more poorly answered by the entire cohort: this is particularly evident on the pre-instruction assessment scores (figure 3(a)) where the spread of total scores is wider. Although a complete item-by-item analysis of differences in male/female response choices is beyond the scope of this paper, we do highlight a few illustrative examples, chosen by considering those items that lie furthest from the unit line in figure 3, i.e. those items with the largest gender gap pre-instruction or post (or indeed both). These are in no way intended to be comprehensive, but rather representative of the complexity of the data.
Table 4. Proportions of male and female students correctly answering particular items on the pre- and post-instruction tests.

| Item | Institution | Pre score (%) Males | Pre score (%) Females | Post score (%) Males | Post score (%) Females |
|------|------------|---------------------|-----------------------|----------------------|------------------------|
| 1    | Edinburgh  | 85                  | 78                    | 93                   | 89                     |
|      | Hull       | 81                  | 50                    | 97                   | 100                    |
|      | Manchester | 92                  | 83                    | 95                   | 97                     |
| 2    | Edinburgh  | 65                  | 40                    | 81                   | 62                     |
|      | Hull       | 58                  | 33                    | 75                   | 17                     |
|      | Manchester | 70                  | 40                    | 85                   | 75                     |
| 13   | Edinburgh  | 54                  | 31                    | 91                   | 80                     |
|      | Hull       | 61                  | 33                    | 69                   | 50                     |
|      | Manchester | 80                  | 52                    | 93                   | 77                     |
| 23   | Edinburgh  | 78                  | 40                    | 85                   | 64                     |
|      | Hull       | 75                  | 50                    | 86                   | 50                     |
|      | Manchester | 85                  | 63                    | 96                   | 73                     |

3.2.1. Item 2. On the instrument is a companion question to the very first question, both of which are descriptive (i.e. no diagrams or figures presented in either the question or the possible answer choices). In the first item, two balls are dropped from the same height at the same time, with one being twice as heavy as the other. Respondents are asked to choose from several options for the relative time it will take the two balls to hit the ground. Item 2 uses the same two balls, this time rolling off a horizontal table at the same speed. Students are asked to choose from five statements describing how far away from the table the balls hit the ground. In both cases, the correct response is that the time (in the first case) and the distance (in the second) are the same, with the common principle in both questions being that objects of different mass fall at the same rate.

Despite the similarity in these pair of questions, the response profiles from male and female cohorts at each of the three institutions illustrate consistent and puzzling differences for pre- and post-instruction responses, as shown in table 4. For item 1, there is a slightly higher fraction of male students who initially get the question correct (significantly so for Hull students, but with the caveat of small number statistics). Post-instruction there is significant improvement, and effectively no difference in the fraction of male and female students who get the question correct (which we subsequently denote as ‘the item gender gap’). For item 2, which is initially answered far less well by students at all three institutions, the pre-instruction item gender gap is evident and persists post instruction. Furthermore, there is no obvious incorrect answer choice chosen preferentially over others. Such response profiles—consistent across institutions, yet distinct between two linked questions—are puzzling and merit further investigation via qualitative study.

3.2.2. Item 13. Is a descriptive question that asks students to consider the forces acting on a ball after it is thrown vertically upwards from someone’s hand. The correct answer is that the only force acting on the object after it has left the thrower’s hand (in the absence of air resistance) is the force of gravity alone. Well-documented student beliefs about this scenario are that the force of the ‘throw’ persists (either as a constant or steadily decreasing force) even after the object has left the thrower’s hand.

As shown in table 4, this item also exhibits a noticeable item gender gap, for both pre- and post-instruction tests (though much diminished in the post-instruction test). Here, the dominant incorrect choice is that the force of the throw gradually ‘runs out’ during the upward motion, a belief still held by approximately one quarter of female students post-instruction.
3.2.3. **Item 23.** Forms part of a set of four consecutive items and is a very visual scenario, with schematic diagrams in both the question stem and the answer choices. It is a representative example of a number of items on the instrument: it asks students to consider the effect of (the removal of) a constant force acting at right angles to the initial motion. These sorts of questions, combining uniform motion in one direction with an accelerating force applied in one perpendicular, tend to cause students a significant challenge.

Item 23 in particular exhibits a large item gender gap pre-instruction (table 4) with only marginal improvement by both male and female cohorts post-instruction, thus resulting in a significant post-instruction item gender gap. The pattern of post-instruction incorrect responses of female students on this item shows a spread across the range of all four possible incorrect options.

These examples, together with the proportion of male and female students getting other items correct, and the resulting answer choices distributions, illustrate a complex picture, with no obvious or immediate general patterns of behaviour between male and female cohorts. We intend to try and unravel some of these issues in an on-going qualitative study that will use some of these items (or equivalent/isomorphic questions) as the basis for discussion in structured interview scenarios.

3.3. **Exam performance**

Of course, the FCI covers only part of the course material. Looking more widely, we may wish to consider the existence, or otherwise, of performance gender gaps on final examinations (typically the principal assessment component for all of these courses). In doing so, we accept the inherent limitations that exams often test a degree of knowledge (‘bookwork’) and other measures of proficiency as well as the conceptual understanding that forms the focus of the FCI. Nevertheless, for the same cohorts of students at each of the three institutions in this study, we find that there is no statistically significant difference in examination performance for male and female cohorts, as determined by a $t$-test at the 5% significance level.

4. **Discussion**

Our results present a picture of a persistent and very noticeable gender gap in both pre- and post-instruction FCI performance. This is true across all three institutions, and appears to be independent of the precise details of method of research-informed instructional delivery. Data from the University of Manchester over the past 5 years show a similar consistent picture over time [26]. The presence of such a gap pre-instruction is entirely consistent with previous work reported from the US context [5, 8, 7, 27], and the persistence of it post-instruction consistent with some [7, 27] but not other reports [5].

A comparison with the Minnesota data [8] suggests that many of the same items have a gender difference for students from both the UK and USA. Since we can extract only the fraction of correct answers from their paper, we can not judge whether the same distractors have been chosen in both cases. It would be quite interesting to have some data from a country with a very different educational system, to study the effect of cultural differences on the gender difference we have noted. The only published work we are aware of is on Turkish high school students [28], and shows little gender difference, but at a very early stage of education and concomitant low level of achievement, making it less relevant to the current discussion.

Our analysis raises the question whether the FCI instrument is partially to blame for these difficulties. There has at least been one attempt to make a less male-stereotyped version of the FCI [29], though results using this were largely inconclusive due to a low overall
attainment both pre- and post-instruction on the refined instrument, obscuring any potential real effect. Moreover we see substantial differences in our results on questions that do not have gender-stereotyped contexts.

Potentially the most significant result in this study is the finding that the lowest performing quartile on the basis of the pre-instruction test comprises approximately half the total number of female students in a given cohort (for Manchester and Edinburgh data). Furthermore, the majority of these female students (70% for Edinburgh and 60% for Manchester data) remain there in the post-instruction assessment. This should serve as a warning: instruction that otherwise looks highly effective—as judged by peers, pass rates and even ‘headline’ measures of effectiveness such as cohort-averaged improvement between pre- and post-instruction testing—may be far from a panacea for some of the particular sub-groups one would like to target especially.

Notwithstanding the persistence of the gender gap on the FCI instrument, we believe that the outlook over the longer period of a student’s studies is not quite so bleak. Newtonian mechanics is only part of the first year of study, and there is some evidence to suggest that there is a more equal distribution between quartiles based on exam marks, especially when we look later in their programmes of study. In a typical US programme [7, 27] it has been argued that the gender effects increase. In the UK, female students who persist to the end of the undergraduate course tend to do well, but there is concern about the loss of students on the way.

5. Conclusions

We have found a significant and persistent performance gender gap within three separate student cohorts in introductory physics at three different institutions. The gap is reduced, but not eliminated after instruction, which is in line with some (but not all) research findings from the equivalent US context. We find that approximately half the female students in a particular class are initially in the lowest performance quartile (on the basis of pre-instruction assessment with the FCI) and that the majority of these students remain there at the time of post-instruction testing with the same instrument. Analysis of individual items shows that male students outperform female students on practically all items on the instrument, both pre- and post-instruction. Looking at other assessments taken by these students in their respective courses, specifically examinations at the end of the course, we find no significant gender gap in performance at any of the three institutions in this study.

This study opens up several interesting avenues for further work. Clearly, having identified a potential problem, we need to find out more about causes and potential remedies. Our first step is to follow up with a qualitative approach using structured interviews to identify some of the factors and issues that make a difference in the students’ performance. At the same time we intend to continue to make use of the FCI to monitor performance in this small area of the curriculum, and study the effects of specific interventions on the performance of male and female students.

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