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Students' Representational Fluency at University: A Cross-Sectional Measure of How Multiple Representations are Used by Physics Students Using the Representational Fluency Survey

Matthew Hill & Manjula Devi Sharma
The University of Sydney, AUSTRALIA

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To succeed within scientific disciplines, using representations, including those based on words, graphs, equations, and diagrams, is important. Research indicates that the use of discipline specific representations (sometimes referred to as expert generated representations), as well as multi-representational use, is critical for problem solving and developing understanding. This paper consolidates these ideas using the Representational Fluency Survey (RFS) over two years with 334 students at The University of Sydney. Analysis shows that there was a significant difference between the representational fluency of the 1st year Fundamental and Regular students (low level 1st year physics courses) compared to the 1st year Advanced, 2nd year, 3rd year and Postgraduate level students. The existence of this distinct gap is further supported by evidence from qualitative coding that students with a high level of representational fluency use a greater number of representations and more visual and symbolic representations to explain their answers. There is no mention of such an overall trend of variation of representational use in extant literature, largely because there have been no studies that compare representational fluency across closely spaced levels of physics, or science, learning.

Keywords: physics education, representational, fluency, graphs, equations, diagnostic testing, multiple representations

INTRODUCTION

It has regularly been identified that participation in scientific disciplines is based on the interplay between conceptual understanding, the use of representations and

Correspondence: Matthew Hill,
The Sydney University Physics Education Research group, School of Physics, A28, the University of Sydney, NSW 2006, Australia.
E-mail: m.hill@physics.usyd.edu.au
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experiential learning (Duschl & Osborne, 2002; McCormick, 1997). To succeed within the discipline, using multiple representations becomes central to problem solving, understanding, and communicating. Research on multiple representations range from in-depth investigations of students' use of specific representations to how students can attain a greater competency with a range of representations. This paper focuses on the later. We examine representation use, through an analysis of the results of the Representational Fluency Survey (Hill, Sharma, O'Byrne, & Airey, 2014), consolidating ideas of *metavisualisation* (Gilbert, 2004), *representational competence* (Hand & Choi, 2010; Stieff, Hegarty, & Deslongchamps, 2011) and *metarepresentational competence* (diSessa, 2004) which have emerged in the last decade.

State of the literature

- When learning in order to participate scientific disciplines, students must gain both discipline-specific conceptual knowledge and the ability to utilise the representations (e.g. graphs, words, and equations) used for communication and problem solving.
- The ability to use multiple representations has been referred to using a variety of terms with similar yet distinct meanings such as metavisualisation, representational competence, and metarepresentational competence.
- There has been limited large-scale, quantitative measures related to representational use, and these tend to focus on a specific subset of representations in a particular context as opposed to generic representational fluency.

Contribution of this paper to the literature

- Representational fluency is defined and suggested as an amalgamation of metavisualisation, representational competence, and metarepresentational competence.
- The Representational Fluency Survey, a published diagnostic test, is used to measure the representational fluency of closely spaced levels of physics learning experience at university identifying that many students may need to greatly improve in order to successfully continue to learn physics.
- Characteristics of representational fluency are determined and compared to previously identified traits in literature.

Theoretical framework: Multiple representations

There is extensive literature on the role and use of multiple representations. Multiple representations refer to the combination of formats used to generate, process, or present information (Gilbert, 2004). In the context of the natural sciences, generic examples include graph, word, equation, and diagram based representations along with specific discipline representations, for example Lewis structures in chemistry and free body diagrams in physics. Collectively, these form part of the disciplinary community of discourse, defined by a common language expressed through shared understandings of representations (Driver, 1994). As students progress in their studies, instructors and students use multiple representations to communicate, develop understandings, and demonstrate understandings. Appropriate use of multiple representations in instruction can make information more memorable (Aldrich & Sheppard, 2000), more easily processed in working memory and integrated with prior knowledge in long term memory through overcoming cognitive load limitations (Ainsworth, 2006), and portray relationships that are not easily identifiable (Goldman, 2003; Roth, Bowen, & McGinn, 1999).

When focussing on student use of multiple representations, especially in the sciences, student difficulties are associated with both understanding the representations themselves as well as how to reason using representations while learning and during problem solving. This is demonstrated through the considerable research in the area of "graphicacy", or student use of graph-based representations, essential for science students (Roth et al., 1999). Focusing on physics, the difficulties with graphing become more pronounced as the need to use them appropriately becomes more critical (Beichner, 1994; Woolnough, 2000; Wu & Krajcik, 2006). Student difficulties are associated with interpretation of the axes, understanding the gradient and failing to understand why two different graphs that look the same, but have different variables, don't necessarily represent similar situations (Beichner, 1994). Interestingly, student understanding is sensitive to context, for example, many are unable to answer graphical questions which include the same level of mathematics which they have already demonstrated proficiency in, in another context (Leinhardt, Zaslavsky, & Stein, 1990). Such inconsistency is part of how students negotiate tenuous understandings as they co-construct conceptual knowledge in physics (Britton, New, Sharma, & Yardley, 2005). Experience also suggests that some students simply lose confidence when a question includes a graph, or requires them to use a graph, leading to a higher level of stress and incorrect answers (Engelbrecht, Harding, & Potgieter, 2005). There has been a range of investigations into student difficulty with other representations key to physics including equation-based (Bieda & Nathan, 2009), diagram-based (Pollock, Thompson, & Mountcastle, 2007) and word-based representations (Dufresne, Gerace, & Leonard, 2004; Jacobs, 1989).

To succeed within a discipline, students do not simply need to be competent with one representational format, rather to shift their tenuous and often inconsistent understandings, towards those that are more scientifically congruent. This inherently means, choosing and using appropriate individual representations and integrating between them when needed. Consequently, while continued research into individual representations is immensely valuable, the field of multiple representation research has continued into broader descriptions of representational use, grouping representations as "modes" and even investigating inter-modal and multi-modal use. Three perspectives on integrating representational use are described briefly here, followed by a discussion on representational fluency.

Gilbert (2004) suggested that different representations could be grouped into five "modes" including concrete, verbal, symbolic, visual, and gestural and that *visualization* describes making meaning out of representations. *Metavisualization* is the metacognitive side of this, where students can "acquire, monitor, integrate, and extend, learning from representation" (Gilbert, 2008, p. 5-6).

The second perspective, *representational competence* utilises Gilbert's (2004) framework. Representational competence focuses on the domain specific constellation of representations. Studies in representational competence isolate representation use specific to a domain and then investigate scaffolding student attainment of such representational use (Kohl & Finkelstein, 2005; Kohl & Finkelstein, 2006b). Representational competence begins with using representations authentically (Roth & Bowen, 1999) and being able to extract information from given representations (Shafrir, 1999) but has been extended to cross-representational use where multiple modes of representation in Gilbert's model (2004) are used in student answers and instructional material (Hand & Choi, 2010; Stieff et al., 2011).

Metarepresentational competence (MRC), as the name implies, is the metacognitive aspect of representational competence where individuals understand the rationale behind representations and includes creating new representations and learning or utilizing new representations quickly (diSessa, 2004). Important is the *why* of a particular representation, more technically referred to as the representation's affordance (Fredlund, Airey, & Linder, 2012; Gibson, 1977). The ability to choose the most appropriate representation for a given situation is a skill of those with metarepresentational competence (Dufresne et al., 2004)

This paper consolidates the above literature by relating to all three different perspectives on integrating representational use. What is being measured by the Representational Fluency Survey will relate to each of Metavisualisation, representational competence, and metarepresentational competence. This means that none of these terms alone is able to fully encompass what is being measured and investigated in this paper.

Representational fluency used by Nathan, Stephens, Masarik, Alibali, & Koedinger. (2010) is suggested as an integration of these perspectives. Lesh (1999) explained that representational fluency facilitates students to be analysing problems and planning multi-step solutions, justifying and explaining representational use, assessing progress, and "integrating and communicating results in forms that are useful to others" (p 331). Individuals who are representationally fluent have a competence in domain specific representations and the metacognitive skills to apply their knowledge of representations effectively (Uesaka & Manalo, 2006). Proficiency at translating between representations, a characteristic of metavisualization, is also a defining characteristic of representational fluency (Bieda & Nathan, 2009; Nistal, VanDooren, Clarebout, Elen, & Verschaffel, 2009). Representational fluency is a genre of thinking important for all science students and despite the dependence on discipline-specific representations, the representational thinking component allows for it to be transferable across scientific disciplines. Mathematics educators capture representational fluency as *representational flexibility* (Thomas, Wilson, Corballis, Lim, & Yoon, 2010). Hill et al. developed the Representational Fluency Survey (2014) to measure representational fluency. The focus is on scientific multiple representations nuanced for a physics specialization, that is, representations for physics and wider science incorporating as a relevant skill for physics students, encapsulating the transfer of representational use.

Significance of the study

Previous research involving representations in science typically uses individual problems, or sets of problems focussing on particular facets of reasoning (Kohl & Finkelstein, 2006a; Kohl & Finkelstein, 2008; Meltzer, 2005; Woolnough, 2000). For example, an important contribution was when Meltzer (2005) varied the representation used to portray a physics question to compare how students would respond (similar to Kohl & Finkelstein (2005)). Many studies are predominantly observational data allowing for qualitative description of student behaviour often presented through case studies (Fredlund et al., 2012; Rosengrant, Van Heuvelen, & Etkina, 2006; Sia, Treagust, & Chandrasegaran, 2012; Tytler, Prain, Hubber, & Waldrip, 2013). In particular, studies in metarepresentational competence (diSessa, 2004) and metavisualisation (Gilbert, 2008), to our knowledge, are largely qualitative in nature.

There have been some large-scale, quantitative measures related to representational use, however these focus on a specific subset of representations in a particular context. Two examples are the Test of Understanding Graphs in Kinematics (Beichner, 1994), which focuses on the one representation, graphs, and difficulties associated with use in the context of kinematics, and the Perdue Spatial Visualization of Rotation (Bodner & Guay, 1997) which measures spatial ability in introductory chemistry.

The RFS allows for a large-scale, quantitative measure of the broad area of representational fluency, rather than one category of representations. Therefore, this is the first study to allow for direct comparisons to be made across closely spaced levels of physics learning experience at university. The importance of this is two-fold, firstly, that this study has been able to determine that there is a significant gap in representational fluency between cohorts of 1st year students which may result in many students being unable to continue with physics in later years, and secondly, the results have allowed for a more quantitative understanding of what constitutes representational fluency to be developed which is significant for instructional design in this area.

Both of these areas of significance are investigated through the two research questions of this paper.

- *Research Question 1* – How does representational use as measured by the Representational Fluency Survey vary across different cohorts of university physics students?
- *Research Question 2* – What are the characteristics associated with proficient use of representations

Purpose of the study

To answer these research questions, this paper presents an analysis of the results of the RFS administered cross-sectionally over two years to different student cohorts from first year students with minimum background in physics to Postgraduate physics students. The first section (Part 1: Research Question 1) compares results across the different cohorts to examine trends in students' representational use. The aim is to find whether there are distinguishable differences or a gradual development of representational use.

The second section (Part 2: Research Question 2) uses the framework of representational modes (Gilbert, 2004; 2005) to characterise representational use. The way that students combine representations and whether particular modes, especially more sophisticated modes, are used by particular groups of students will also be investigated.

This paper is presented in two parts. Each part focuses on one of the research questions. The methodology that applies across both parts is outlined in the methods section, then within each part there are separate sections for analysis methodology, results, and analysis with implications. After the two parts there is a general discussion drawing together the two research questions.

METHODS

The instrument

The Representational Fluency Survey (RFS) (Hill et al., 2014) is a published diagnostic test designed to measure the representational fluency of university-level physics students. The reliability and validity of the test have been demonstrated in a previous publication (Hill et al., 2014). Face and content validity were confirmed using student feedback and interviews, and regular collaboration with a physics education expert panel. The RFS has seven multiple choice items, six of which are recommended for general use, have satisfied the criteria for standard statistical tests (difficulty index, point biserial coefficient and Cronbach's alpha).

Of the survey's seven items, the context of three items is deliberately not physics, and the remaining have physics contexts. The disciplinary information needed to answer both the physics and non-physics items is contained within the item. The items have specifically been designed and tested such that students who have studied senior high school science subjects and mathematics are able to interpret the context. The difficulty that the student has with each item is associated primarily with the representations used. Hence the RFS probes students use of representations, and is a representational survey nuanced for physics students. Respondents are asked to choose an answer for each item and "provide brief information which supports the answer you have chosen". Table 1 lists the characteristics of each item and the representations used in each. Student responses to most items are presented in the Figures listed in the final column of the table. The full survey is found in Appendix 1.

It is important to note that four items of the RFS do come from the physics discipline. This does not invalidate the claim that the RFS measured

Table 1. Characteristics of each item of the RFS emphasising the representations used in each

Item Number	Question description	Completed item presented in this paper
I	Words explain that "acceleration is a measure of how velocity changes with time" and asks participants which of five graphs shows the greatest change in velocity. Five simple line graphs are given.	Figure 1
II	Words describe the motion of a coin tossed into the air. Eight options are given (in words) that are to be chosen to describe the force on the coin at various points in the motion.	Figure 6
III	Two bar graphs are given displaying the proportions of boron and oxygen in the compound boronic oxide by mass and by number of atoms in the compound. In words, the question asks for the mass of an oxygen atom compared to boron and there are four numerical (decimal) answers to chose from.	Not pictured. See Appendix 1
IV	Words introduce students to a "nomogram" and give an example of a set of information that is discernible from the graph. A nomogram (graph) is presented with two parallel scales with a third at an angle between them. Participants are asked to find a particular numerical reading using the graph.	Not pictured. See Appendix 1
V	Words explain the motion of two competitors in an orienteering tournament. There is substantial extraneous information not necessary to answer the question. The question asks which competitor will reach the checkpoint first.	Figure 4
VI	Words explain different types of plant in a rainforest and particular needs. Two graphs give information about rate of fern growth and height compared to light intensity for an unknown plant. Five descriptions of plants are given for participants to choose from.	Figure 5

Note: The last column lists where student responses are presented in this paper
The original survey included seven items however the authors recommended against using the original item six.

representational fluency independent of content knowledge. The development and testing of the RFS affirmed that the difficulty that students have with each item is associated with the representations used, the theory behind each item is learnt at a pre-university level in Australia (Hill et al., 2014).

The first research question probing variation in representational use amongst different cohorts of students was approached using an analysis based on a three-tier marking criteria, quantitatively comparing student groups. The second research question needed in-depth analysis involving qualitative coding of the rich data. The two analysis techniques are explained separately within the findings and analysis sections for each research question.

Procedure and the sample

They RFS was deployed with students from first, second, and third year of undergraduate physics as well as Postgraduate students in Semester 1 of 2011 and 2012 at The University of Sydney according to university Human Ethics Committee protocols. Within first year we have 3 separate cohorts, Fundamental, Regular, and Advanced. These cohorts have very different experiences prior to university. The 1st year Advanced students scored exceptionally well in their senior high school studies, have high physics marks and generally have engaged in a range of extracurricular and enrichment programs which are not part of the mandatory school curriculum. The 1st year Regular students also did physics in senior high school but did not do so well and the 1st year Fundamentals students have done limited or no physics in the final years of high school. Each of these groups have a different level of 'physics learning experience' which includes a combination of class time, personal study and engagement from educational professionals. The 'physics learning experience' of all the cohorts then progresses from 1st year Fundamentals, 1st year Regular, 1st year Advanced, 2nd year, 3rd year, to postgraduates. This progression is reflected in an increasing trend on performance on conceptual tests, increasing linearly with the levels of physics learning experience (Sharma et al.,

Table 2. The number of student responses from each level of physics learning experience across 2011 and 2012

Level of physics learning experience		2011	2012	Total
	Fundamental	30	15	45
1st Year	Regular	31	30	61
	Advanced	31	30	61
2nd Year		32	40	72
3rd Year		36	33	69
Postgraduate		15	12	27
Total		175	160	335

2010; Tongchai, Sharma, Johnston, Arayathanitkul, & Soankwan, 2011). Consequently we use the phrase, 'levels of physics learning experience' to refer to these six different cohorts of students. A total of 335 student responses are used in this study. Table 2 shows the numbers from each level of physics learning experience for 2011 and 2012. There was no overlap in students participating in the study across the two years.

PART 1: RESEARCH QUESTION 1

Analysis methodology

To answer the first research question, we developed the specific three-tiered marking scheme shown below. The marking scheme captured whether students were obtaining the 'correct answer', tier I.1, but more importantly whether students use of representations were appropriate, tier I.2, and consistent, tier I.3. The three-tiered scheme (from Hill et al., 2014) is as follows:

- I.1 Selecting the correct answer to the representationally rich multiple choice question irrespective of what was provided in support of the answer. (Referred to as the student's "*answer*").
- I.2 A scientifically congruent explanation (using any representation), relevant to the question and leading to the answer. It may not always end up producing the answer chosen by the student (referred to as the student's "*explanation*").
- I.3 Consistency between the chosen "*answer*" and the "*explanation*" in that the explanation leads to the selected multiple choice answer, and can use any representation (referred to as a "*consistent/inconsistent explanation*").
- In this way, it is possible for students to get a score of zero, one, two, or three for each item.

The following example illustrates the marking scheme using three student responses for item I. Figure 1 shows responses from Student A who selected the correct multiple choice answer "B", provided a scientifically congruent explanation using equations and was consistent, scoring the full 3 marks. Student B did not choose the correct answer (chose "C") but did offer a scientifically congruent explanation, "Area under graph is greatest" that was relevant and leading to the correct answer. Student B's explanation did not align with the answer they selected making it inconsistent. Therefore Student B scored one mark for the explanation under criteria I.2. Similarly, Student C received only one mark. This student's answer "D" was consistent with the explanation: "As the rate of acceleration is increasing with time, the velocity is increasing at an ever increasing rate". But the answer was incorrect, and the explanation, while a true statement in the context of the question,

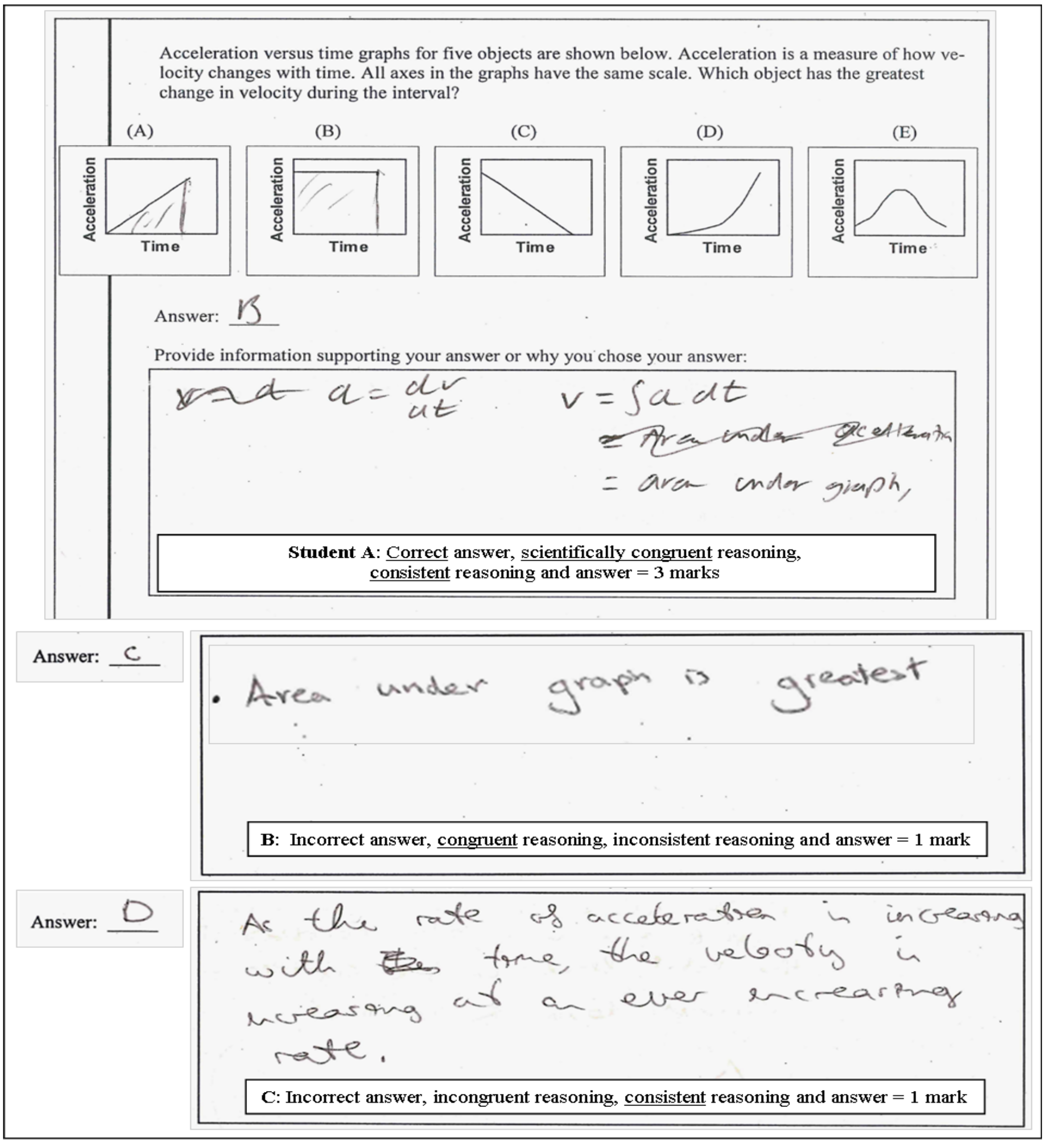


Figure 1. Three student (A-C) responses to item one illustrating representational use and demonstrating the use of the three-tier marking system

was not in any way leading to the answer and therefore the second-tier mark, I.2, could not be awarded.

The three tiers allow for different elements of representational use to be incorporated. One element is attaining the correct answer (tier 1) requiring students to utilise the presented information and to commit to an appropriate answer which can be done by implicit or explicit use of representations. Another element, is in providing an explanation (tier 2), students need to choose and use representations authentically, to make meaning of the process. This is often demonstrated through student shading and markings on visual representations presented in the question or through student sketching. The last element is when students offer a consistent explanation (tier 3) with their chosen answer, they are displaying transfer between their chosen representation in the explanation to the representation used in the question.

The next stage of the analysis was determining if the distributions for each levels of physics learning experience are normal and selecting the appropriate tests for comparing means. Kolmogorov-Smirnov tests of normality revealed that the distribution of the survey score was not normal for all groups of students. Consequently, the Kruskal-Wallis tests (non-parametric) were used to determine whether there is a significant difference between any of the means (Field, 2003). Post-hoc analysis to identify where the difference exists between particular means was done using Games-Howell tests (Toothaker, 1993). Man-Whitney Tests with Bonferroni Corrections were completed to ensure the reliability of the Games-Howell tests but the results are not presented in the paper as there was no deviation from the Games-Howell results.

The mean RFS score for each level of physics learning experience were compared to investigate representational fluency as a whole The results were compared to conceptual surveys completed at the same institution with the same levels of physics students from previous years. This was to validate that the RFS was measuring representational fluency distinct from content knowledge. The mean scores on each tier of the RFS for each level of physics learning experience were also compared to investigate whether the trends present with the overall RFS score are mirrored in any of the tiers.

Results: Comparing means

First we plotted the means for the different levels of physics learning experience. The results are presented in Figure 2b. The striking point to note is that the trend is not linear. This is in contrast to the linear trend these groups exhibit when results from conceptual surveys are compared in a similar manner, demonstrated in Figure 2a. These two concept tests, the Force Motion Concept Evaluation (Thornton & Sokoloff, 1997), and the Mechanical Waves Conceptual Survey (Tongchai et al., 2011) are established tests which have been used at the institution in the last decade to measure conceptual knowledge across different groups of physics students. Results from these tests being used on these groups have been published (Sharma et al., 2010, Tongchai et al., 2011) and can therefore be used to compare with the representational fluency of the current cohort of students. While the conceptual ability of the levels of physics learning experience at The University of Sydney increases linearly (as depicted by the R^2 values in Figure 2: a.), this linearity is not reflected in RFS scores which show the student groups forming two bands, with a gap in between. The four highest levels of physics learning experience (from 1st year Advanced to Postgraduate students) form the upper band and the lowest two levels of physics learning experience (1st year Fundamentals and Regular) form the lower band.

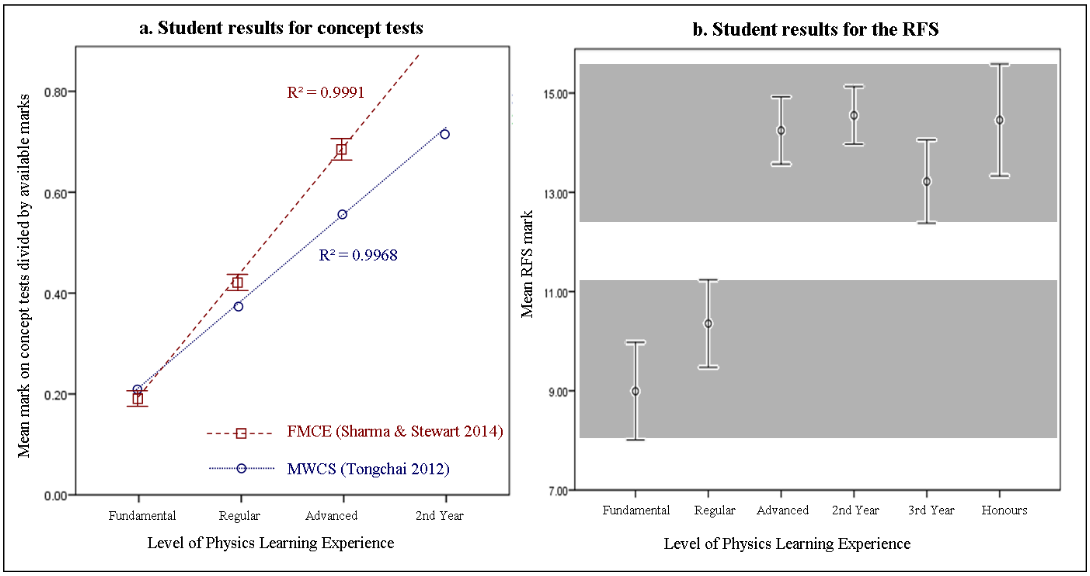


Figure 2. a. The average student mark from conceptual surveys (linear relationship). b. The average student mark for the RFS (non-linear relationship)

Note: Error bars, where available, depict 95% Confidence Intervals.

The Kruskal-Wallis test reveals a significant difference in the average marks (P<0.001) which is consistent with two clusters as revealed by the post-hoc analysis. The 1st year Fundamental and Regular students typically scored less than 11 out of 18. There was no statistically significant difference between the average mark of these two groups (P=.311). The higher band, consisting of 1st year Advanced, 2nd year, 3rd year, and Postgraduate students, have averages ranging from 13.2 to 14.4. Similar to the lower band, the differences in the means of these four groups is not statistically significant. This relationship is illustrated in Figure 2 through the emphasis of the two bands which take into account the 95% confidence intervals but show the clear difference between the two sets of groups. Games-Howell tests reveal that when comparing any group in the lower band with any group in the upper band there is a significant difference in the mean scores.

Results: Comparing means across each tier of the RFS

The two bands are not only evident when looking at the marks on the whole RFS but also when more detailed data exploration is undertaken. One example is that the bands are evident when student scores for each marking tier are investigated. Figure 3 presents the mean marks for each marking tier for the different levels of physics learning experience revealing again the distinctive lower band (1st year Fundamental and Regular) and higher band (1st year Advanced, 2nd year, 3rd year and Postgraduate) with the gap in between.

Each tier represents a different element of representational fluency. Tier 1 is whether the chosen multiple choice answer, to the representationally rich question, is correct. Tier 2 represents whether any correct and related information using any representation is used. Finally tier 3 is whether an answer is consistent with the information presented in the students chosen representation/representations. Each tier clearly depicts two separate bands. Statistical analysis is consistent with the visual assumptions as every time, the average scores of those in the lower band are not significantly different from each other, but are from each of those in the higher band. Again, none of those in the higher band are significantly different from each other. The tier with the smallest separation is tier 3, the element based on the consistency between student representations and their answer chosen. This is also the tier with the highest average scores so the ceiling effect results in most of the

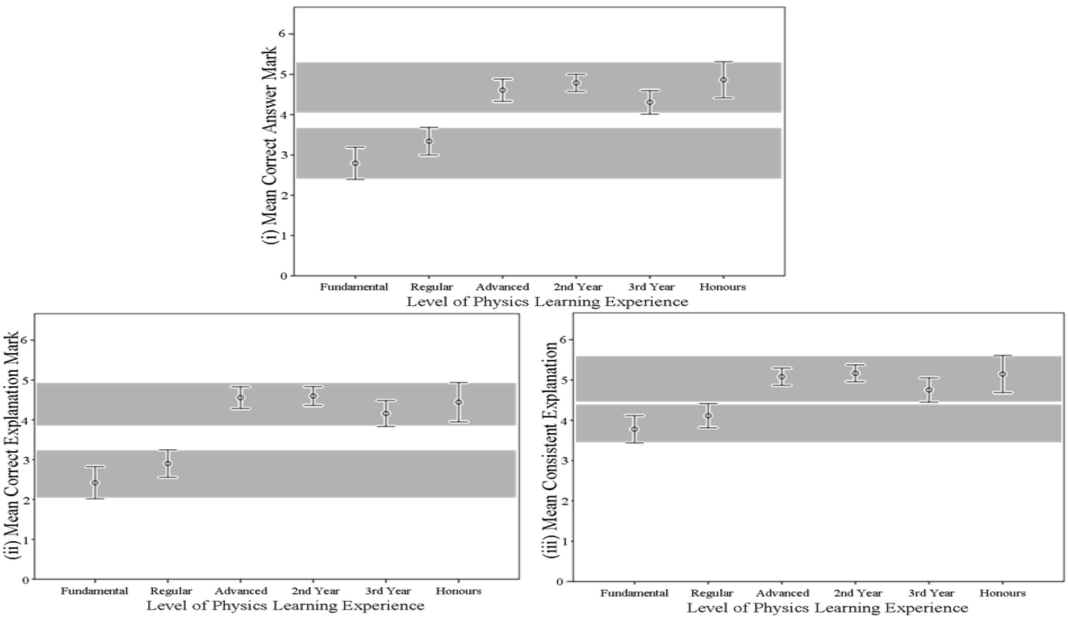


Figure 3. Average RFS marks divided into the three tiers of representational fluency
Note: Each graph shows the same band structure as the average overall marks. Error bars represent 95% confidence intervals.

average scores being closer to each other. Therefore the bands and gap in representational use applies not only to the elements combined but also to the different elements of representational use.

Implications

Our findings indicate that there is a gap in representational use between the 1st year Regular and Advanced learning experience levels. This is somewhat surprising given that these two groups of students are in 1st year of university studies, and they would have experienced the same formal educational high school physics curriculum. Rather than having the same representational fluency as the 1st year Advanced students, the results show that on average the level of representational fluency of the 1st year Regular students is no different from that of the 1st year Fundamental students, who had not studied physics in their final years of high school. It also appears that, the 1st year Advanced students, the 2nd year students, and 3rd year students may have the representational fluency which are present in the highest level (Postgraduate) students as measured by the RFS. These are novel findings which are, to our knowledge, to date not present in the literature.

The results provide evidence against the claim that correctly answering some items was due to learning about the content in previous instruction. Prior instruction results in the linear trend with conceptual tests (see Figure 2a) with Fundamental students scoring lower than the Regular students who in turn score lower than the Advanced cohort. With the RFS, the Regular students are on par with the Fundamental students indicating something beyond conceptual understandings and content knowledge is being measured.

Using the RFS to identity a threshold of representational fluency

The results presented so far reveal a gap in representational fluency, possibly a threshold above which students could be described as "representationally competent". The average student from any of the four higher levels of physics learning experience are above the threshold, indicating high representational fluency (HRF), while those in the lower band are below the threshold indicating low representational fluency (LRF). Very few are in the gap not bound by the 95% confidence intervals presented in Figure 2.

The threshold will need to be in the gap, and for the purposes of answering the second research question we need to choose a value for the threshold. This way of choosing is by no means definitive, but provides a value to work with.

The lower bound of the 95% CI for the lowest scoring HRF group was for the third year students with a lower bound of 12.4, and therefore we have set a boundary minimum for representation fluency as 13. Students who score 13 out of 18 or higher in the RFS can be regarded as displaying high representational fluency. The upper bound of the 95% CI for the highest scoring group in the LRF group is 11.2, so the boundary maximum mark to be regarded as having low representational fluency is therefore 11.

It is important to note that not all students from particular levels of physics learning experience matched the average trend for that cohort of students. For example, while the average mark for the 1st year Regular students was clearly in the category of LRF and the 95% confidence interval was below the gap, there were 17 students who displayed HRF with their RFS mark. Similarly, 8 of the 1st year Advanced students attained a mark of less than 12 demonstrating LRF despite the cohort average of over 14. This is unsurprising as the entry criteria for these cohorts are not strictly enforced, there is student choice. There are students studying Regular physics for example who have the academic achievement to undertake Advanced physics and some students in the Advanced cohort who were awarded a place in the course due to their overall high school results which may include many non-science subjects.

Thus having investigated the first research question by comparing levels of physics learning experience, we have also obtained a threshold mark of 12 out of 18 (66%) on the RFS to help us investigate the second research question.

PART 2: RESEARCH QUESTION 2

The second research question involves examining the characteristics associated with proficient use of representations. The characteristics can be probed by counting the representations to analysing based on representational modes (Gilbert, 2004/2005). Three findings arise from investigating these characteristics of students with high representational fluency:

1. They use significantly more representations;
2. They use a greater variety of representations, which are more scientifically congruent; and
3. They use more representations that are visual and symbolic in nature.

Analysis methodology

Student explanations provided an avenue for a richer, qualitative analysis. Initial close scrutiny of the types and variations of representations used revealed that most were based on graphs, words, equations and diagrams (similar to Meltzer (2005) and Kohl & Finkelstein, (2005)). Consequently, a coding scheme based on these representations was developed. The coding scheme was validated by three researchers with experience in science education varying from four to 25 years. The intercoder reliability was calculated using Fleiss' Kappa. The value of Fleiss' Kappa varied had an average of 0.83 and varied from 0.76 to 0.89 or "substantial" to "almost perfect". Any disagreement between the markers has been investigated and exemplars prepared to maintain consistency of coding. Table 3 shows the final coding scheme. The full sample of student responses was then coded. Figure 4 then

Table 3. Final coding scheme for representational use on the RFS

Representation Code	Description	Responses using this representation include:	Responses which do not satisfy this code:
Graph-based (Symbolic & Visual)	Graphs require content that relates multiple axis. Graphs are both visual and symbolic in nature.	Drawing a graph Drawing lines on a graph to illuminate meaning Marking, circling or shading particular areas on a given graph	Referring to the graph using words: "This can be seen in the right graph"
Word-based (Verbal)	Words provide meaning either through explanation or to present statements of information.	Phrases that contribute to student reasoning including: Working out the answer: e.g. "It seems that the right graph is double the left graph and therefore the higher answer will be correct" Phrases explaining working: e.g. "I did this because..." Phrases explaining the steps: e.g. "Next I solved this by..."	Single word answers: e.g. "Gravity" Comments to the marker: e.g. "I don't know how to solve this problem"
Equation-based (Symbolic)	Equations are most commonly used as working however may also be to present statements of information.	Responses with an equals sign (=) and numerals or pro-numerals on each side. When mathematical operators are used in calculation steps Covers both algebraic and arithmetic equations	Writing numbers on the page distinct from mathematical working Using a mathematical operator as an index of measurement: e.g. "Intensity = 6x10Lux"
Diagram-based (Visual)	Diagrams provide situational context and allow students to visualize the scenario.	Drawing a picture of the scenario Drawing a free-body or flow diagram Drawing a 1D line diagram (similar to a graph with only one axis).	Unrelated pictures or marks on the page Circling or underlining information presented in the question.

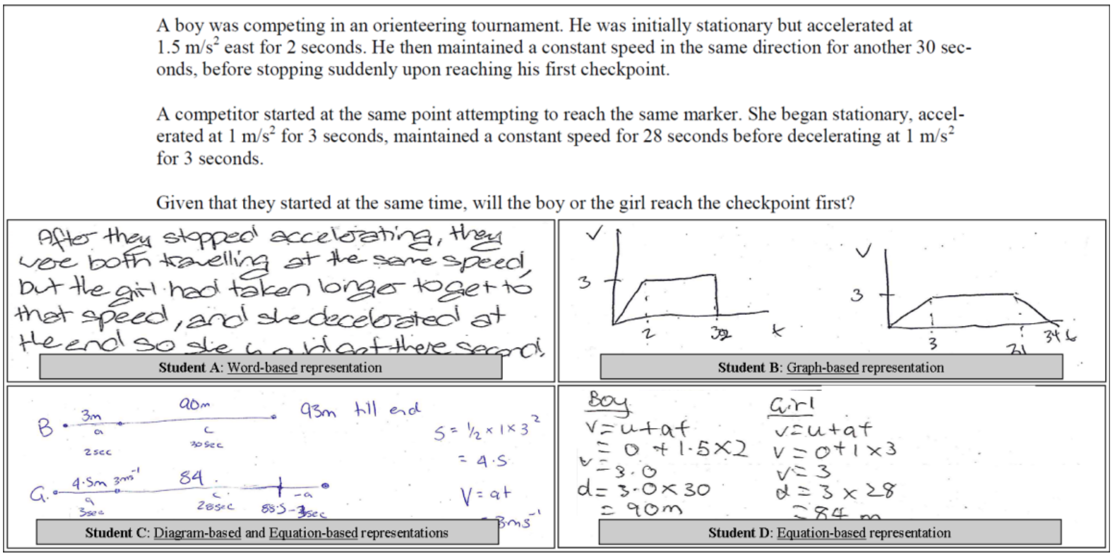


Figure 4. Four responses to item V demonstrating coding of explanations as word, graph, diagram and equation based representations
Note: To be read with Table 3.

Table 4. The distribution of responses using various numbers of representations for each item.

Item	# of Reps	Number of LRF students (n=86)	Number of HRF students (n=74)	Averages
I	0	12	1	LRF = 1.10
	1	57	35	HRF = 1.43
	2	13	17	
	3	4	4	
II	0	6	3	LRF = 1.40
	1	50	37	HRF = 1.30
	2	20	16	
	3	10	2	
III	0	12	4	LRF = 1.05
	1	58	37	HRF = 1.24
	2	16	17	
	3	0	0	
IV	0	27	2	LRF = 1.06
	1	27	10	HRF = 1.79
	2	32	45	
	3	0	1	
V	0	7	1	LRF = 1.37
	1	45	28	HRF = 1.59
	2	29	21	
	3	5	7	
VI	0	33	13	LRF = 0.80
	1	38	18	HRF = 1.47
	2	14	20	
	3	1	9	

provides an example using item V.

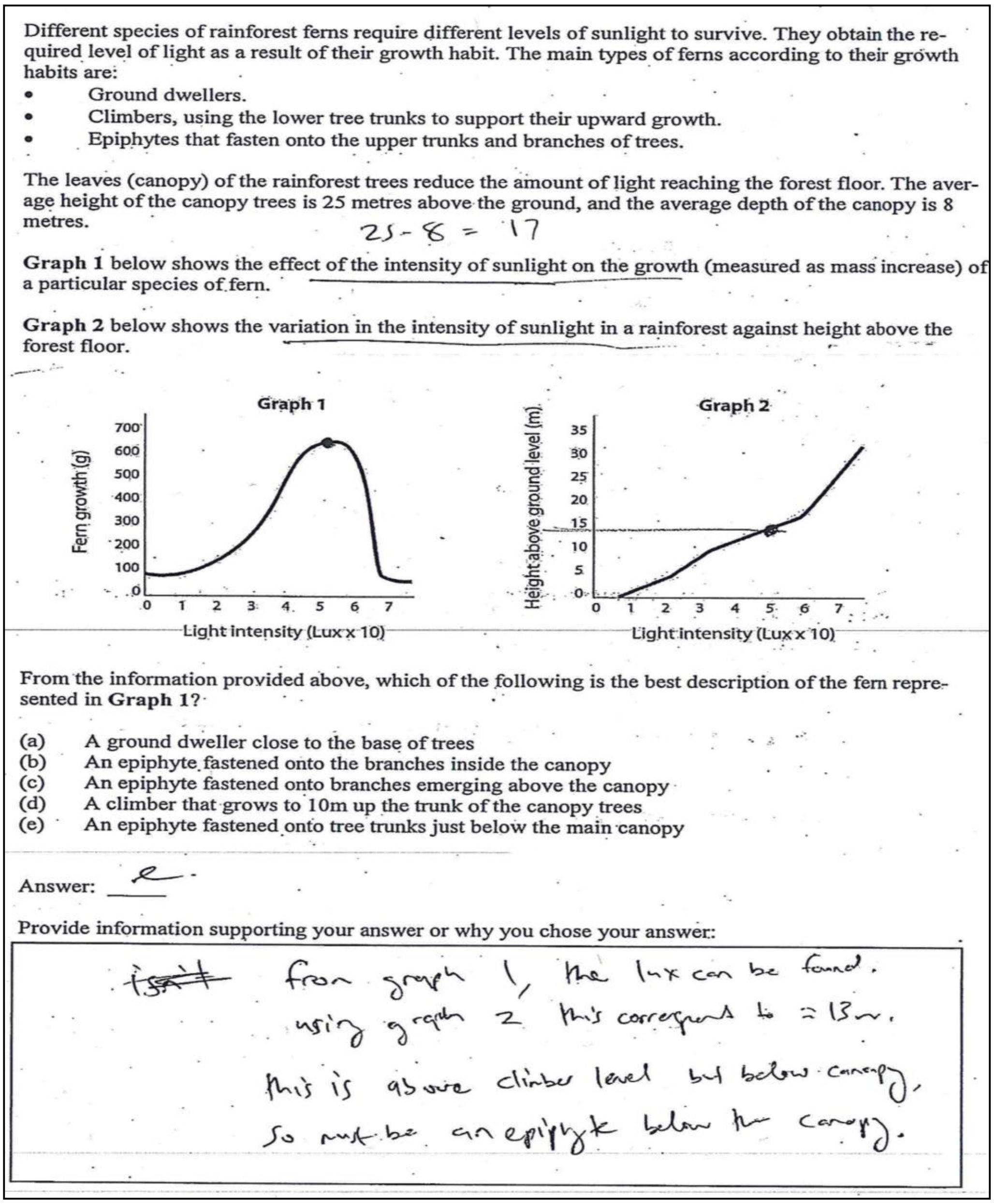
Once the student responses were coded according to the representations present, a number of tests were run comparing averages for HRF and LRF students. These include comparing the number of representations used, the variety of representations used, and most favoured modes of representations from each group.

Results: They use significantly more representations

For each item, the number of representations used by each student was counted. There were no instances where a student used all four representations for an individual item. Table 4 lists the number of representations used by LRF and HRF students for each item.

For example, in answering item I, 12 LRF students gave no explanation or gave an explanation which was not able to be coded as one of the four chosen representations. 57 students used one representation, 13 used two and four students used three representations. This means that on average LRF students used 1.10 representations in explaining their answer to item I. In a similar manner we obtain an average for HRF students of 1.43 representations. Figure 5 shows one of the nine HRF respondents who used three different categories of representations (word, graph and equation based) to construct meaning for item VI.

From Table 4, in five out of six cases the HRF students are using more representations (as a percentage) than LRF students. The exception is Item 2 where on average LRF students used 1.4 representations compared to the average of 1.30 representations used by HRF students. Distinct from each of the other items, for this particular item, using more than one representation was not necessarily correlated


Different species of rainforest ferns require different levels of sunlight to survive. They obtain the required level of light as a result of their growth habit. The main types of ferns according to their growth habits are:

- Ground dwellers.
- Climbers, using the lower tree trunks to support their upward growth.
- Epiphytes that fasten onto the upper trunks and branches of trees.

The leaves (canopy) of the rainforest trees reduce the amount of light reaching the forest floor. The average height of the canopy trees is 25 metres above the ground, and the average depth of the canopy is 8 metres.

25 - 8 = 17

Graph 1 below shows the effect of the intensity of sunlight on the growth (measured as mass increase) of a particular species of fern.

Graph 2 below shows the variation in the intensity of sunlight in a rainforest against height above the forest floor.

From the information provided above, which of the following is the best description of the fern represented in **Graph 1**?

(a) A ground dweller close to the base of trees
(b) An epiphyte fastened onto the branches inside the canopy
(c) An epiphyte fastened onto branches emerging above the canopy
(d) A climber that grows to 10m up the trunk of the canopy trees
(e) An epiphyte fastened onto tree trunks just below the main canopy

Answer: e.

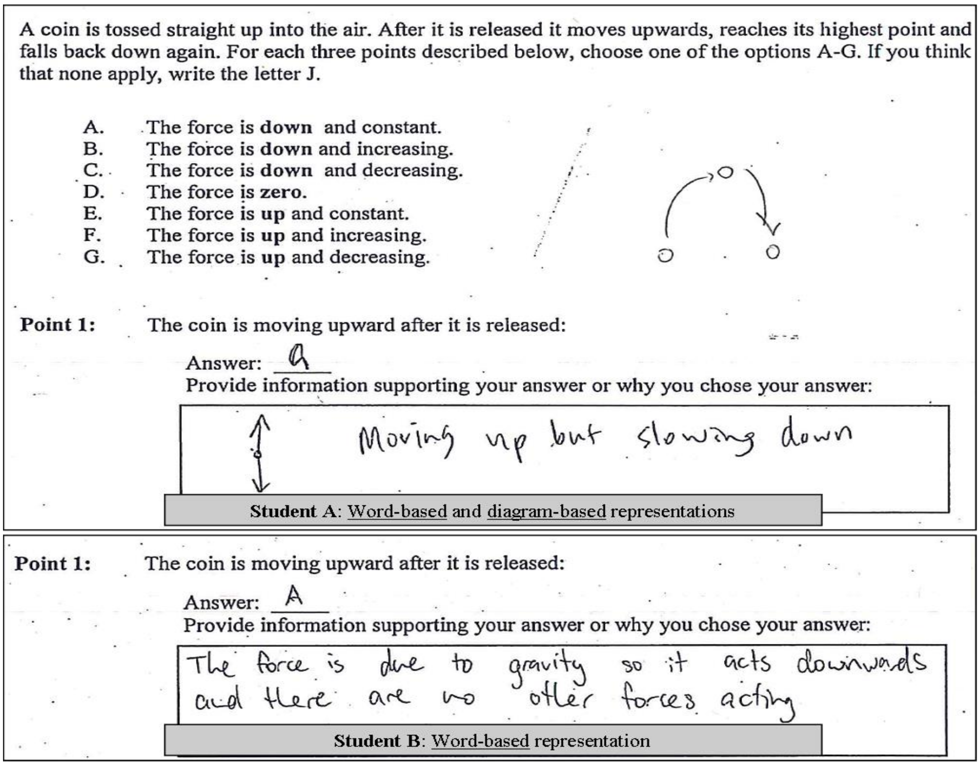
Provide information supporting your answer or why you chose your answer:

~~is~~ from graph 1, the lux can be found. using graph 2 this corresponds to ≈ 13m. this is above climber level but below canopy, so must be an epiphyte below the canopy.

Figure 5. A HRF item VI response demonstrating three different categories of representation (word, graph and equation based)

with students choosing the correct answer ("A"). Figure 6 shows a response from "Student A" who constructs an inaccurate free body diagram where the upward velocity is drawn as a force. This is incongruous with the verbal representation (that the coin is slowing down) which would imply that the force would be down rather than up.

If we total the number of times representations are used across the whole survey, we find that HRF students typically used more representations than LRF students, see Figure 7.


A coin is tossed straight up into the air. After it is released it moves upwards, reaches its highest point and falls back down again. For each three points described below, choose one of the options A-G. If you think that none apply, write the letter J.

A. The force is **down** and constant.
B. The force is **down** and increasing.
C. The force is **down** and decreasing.
D. The force is **zero**.
E. The force is **up** and constant.
F. The force is **up** and increasing.
G. The force is **up** and decreasing.

Point 1: The coin is moving upward after it is released:

Answer: a

Provide information supporting your answer or why you chose your answer:

Moving up but slowing down

Student A: Word-based and diagram-based representations

Point 1: The coin is moving upward after it is released:

Answer: A

Provide information supporting your answer or why you chose your answer:

The force is due to gravity so it acts downwards and there are no other forces acting

Student B: Word-based representation

Figure 6. Two responses to Point 1 of item II

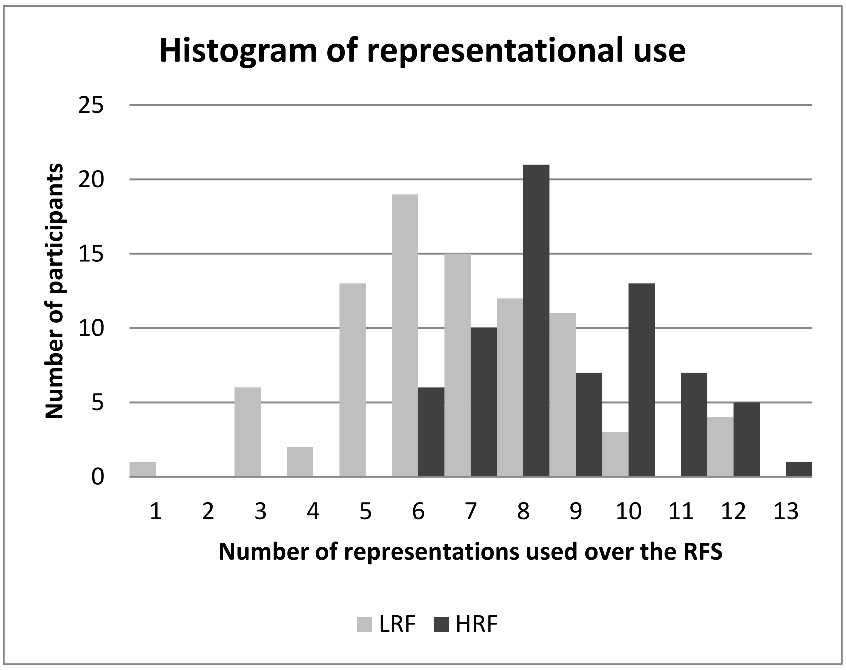


Figure 7. Histogram of the number of students using 1-13 representations across the RFS

Results: They use greater variety of representations, which are more scientifically congruent

To answer the next two sub-questions, a novel way of interpreting and presenting data is explored - a representation quadrant. It combines the four common representations used in problem solving in science aligning with modes described by Gilbert (2005). The written modes are visual, symbolic and verbal (or word-based). The coding in this paper aligns with the three written modes through graph and equation-based representations being of the symbolic mode, graph and diagram-based representations being of the visual mode and clearly word-based representations are categorised as verbal.

The utility of the representation quadrant is that it allows a mechanism for comparing individual student or groups of students with regards to their explanations of individual questions or groups of questions. It is a form of a radar plot where a outer quadrilateral is drawn to represent the frequency of representations used. For example, figure 8 shows a representation quadrant for one HRF student who used word-based representations for five of the six possible times (83%), equation-based representations two of the four possible times, graphs for all four possible times and diagrams one of the three possible times. The representation quadrant illustrates the representations used regardless of whether the responses are correct or not.

A second inner quadrilateral (the lighter shade in figure 8) only includes the representations that were used in a scientifically congruent manner (tier 2 of the three-tier marking scheme) For this particular student, every time they used equation and diagram based representations they used them congruently and this was not the case for graph and word based representations where they were not congruent.

The representational quadrant can also be used for groups of students. Figure 9 compares representational use for LRF and HRF students. It reveals that HRF students use a greater number (shown by the larger area encompassed by the outer quadrilateral) and greater variety (as the corners of the outer quadrilateral are further from the centre marked by the cross hair). Another very clear difference between LRF and HRF students is the degree to which they use representations coherently (as the corners of the inner and outer quadrilaterals are closer together).

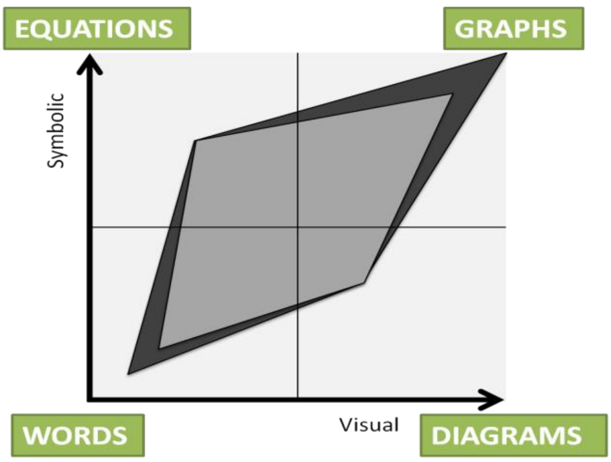


Figure 8. Representation Quadrant for one particular HRF student revealing that word and graph based representations were used most prolifically

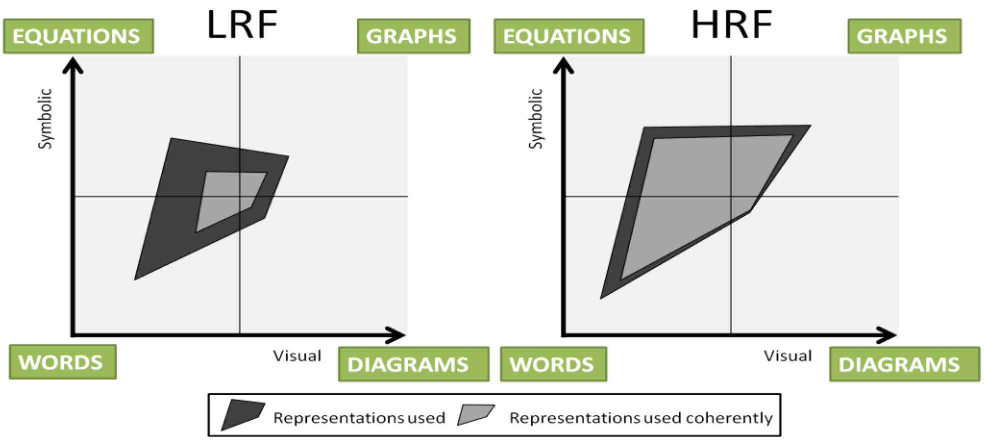


Figure 9. Representation quadrants for LRF and HRF students on average

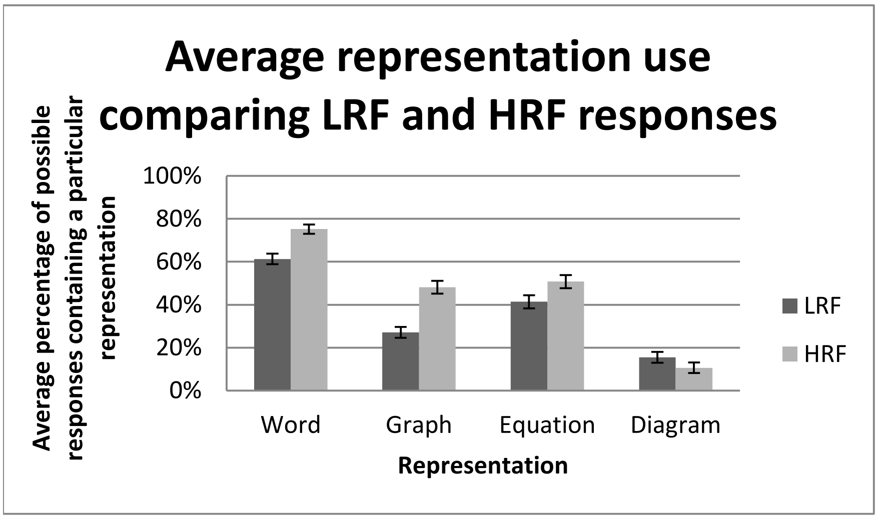


Figure 10. The average representation use of LRF and HRF responses
Note: Error bars are 95% Confidence Intervals.

Results: They use more representations that are visual and symbolic in nature

So far we have shown that HRF students use more representations and they do so in a manner that is more scientifically congruent. But do they choose or prefer to use particular representations more often. Figure 10 compares the average percentage of the word, graph, equation or diagram-based representations used by LRF and HRF students. In the case of words, graph and equation-based representations, there is a significant difference between the average use of LRF and HRF students ($P<0.001$, $P<0.001$, and $P=0.006$ respectively). There was no significant difference in diagram use ($P=0.355$), and the trend is reversed. The effect size is largest for the use of graph-based representations. On average HRF students use almost twice as many graph-based representations than LRF students (Effect Size, Cohen's $d=0.91$). This is compared to the smaller effect sizes of word-based (Cohen's $d=0.63$) and equation-based (0.45) representations.

Considering the use of diagram-based representations, the item that most often elicited a diagram-based response from students was item 2, example shown in Figure 6. For this particular question, diagrams allowed students to visualise the situation, rather than prompt the utilisation of a particularly sophisticated diagram-based representation such as a free-body diagram which assisted in solving the question. It is likely that HRF students generally did not use more diagram-based representations in this manner while LRF students did. Whether this applies more generally needs further research with questions that may require diagrams to reach a solution.

The greatest difference is seen in the use of graph-based representations, which is a representational mode that is both visual and symbolic. This is consistent with Gilbert's (2005) conclusions that novices use more verbal representations and find it harder to branch out into visual and symbolic representations.

To capture our findings, we use the representational quadrant, Figure 11 which is an adaption of Figure 9. The area of the representation quadrilateral which is in the symbolic/visual sectors of the quadrant is highlighted. This itself is a graph-based/visual representation depicting how HRF students may be using symbolic and visual representations more often, and more scientifically congruently than LRF students.

Implications

Our analysis of the RFS shows that HRF students when compared to LRF students:

- Use more representations per question and for the whole survey,
- Use a greater variety of representations and more congruently, and
- Use more symbolic and more visual representations.

While there is research on the importance of representations both individual and multiple for learning science and physics, (Aldrich & Sheppard, 2000; Fredlund et al. 2012; Roth & Bowen, 2003) and conceptual advancements (frameworks) in understanding multiple reputational use (diSessa, 2004; Gilbert, 2008), studies on how these manifest themselves with large sample sizes are rare. This paper demonstrates that the frameworks can be utilised to obtain systematic evidence on how multiple representations manifest themselves. An implication of our study is to continue such large-scale studies.

The finding that integrated use of multiple modes indicates stronger physics knowledge is not new. This point was implied by Lemke (1998), and taken up by various researchers (diSessa, 2004; May, Hammer, & Roy, 2006; Tytler et al,. 2013). However each of these have qualitatively investigated smaller groups of primary and high school level students whereas this paper describes a study with a large sample size of tertiary students to illustrate that the issue of representational

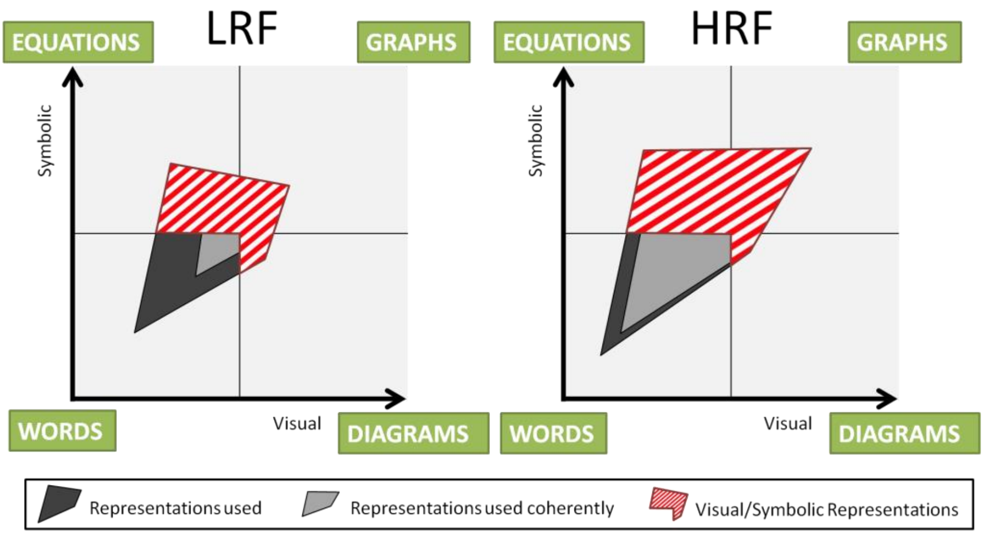


Figure 11. Representational quadrants for the average representational use of LRF and HRF students highlighting the greater use of visual and symbolic representations by HRF students

fluency manifests in particular ways at the university level. As a result, our study confirms the criticality of considering and incorporating multiple representations into the development of instructional methods, in particular to focus on improving representational fluency at a university level. Instruction should both implicitly and explicitly promote students representational use in an integrated way and scaffold towards the often avoided symbolic and visual modes. The lesser use of variety and particularly visual and symbolic representations by LRF students is telling. It may appear, as has been suggested in literature (Dufresne, 2004; Gilbert, 2004), that LRF students feel uncomfortable using representations that are highly symbolic or visual and therefore prefer to use the verbal mode even if the problem is not best solved in this way. Therefore, engaging students with more visual and symbolic representations more often during instruction, complementing words presented both verbally and in written form, may increase their willingness to use such representations scaffolding a greater representational fluency.

Using multiple representations in particular requires students to be able to combine representations meaningfully. To do this, students need to translate between representations therefore teaching strategies designed to facilitate this are consistent with our findings.

GENERAL DISCUSSION

Variation of representational fluency

The results of this paper provide key insights into the use of representations by physics students at university. By analysing the results of the RFS we show a gap in proficiency of representational use. This gap, and clear separation between those who have high representational fluency and those who have low representational fluency is consistent with the notion of there existing a set modes (including representations) that students must be sufficiently fluent with to participate in a disciplinary discourse (Airey & Linder, 2009). The data revealed an unusual point of difference between the cohorts at The University of Sydney. 1st year Advanced students used representations authentically (Bowen, Roth, & McGuinn, 1999) as 2nd year, 3rd year, and Postgraduate (expert) students do, however the 1st year Regular students did not score significantly different to the first year Fundamental students (novices) who had not studied physics in their final years before university.

This suggests that what the RFS is measuring is distinct from conceptual knowledge (Hill et al., 2014) and rather a measure of inter-representational use, or *representational fluency*. Importantly, as representational fluency is not continuously increasing with levels of physics learning experience it emphasises the significance of developing representational fluency among students with no physics background or limited prior success in physics. For 1st physics students who did not excel at high school physics, they will need to develop representational fluency in order to continue to learn at university and participate in the disciplinary discourse (Driver, 1994).

A more particular implication for instruction is that should students continue to avoid, or have trouble with symbolic or visual representations on paper, discerning information in these forms will remain difficult. This has the potential of being a limitation on learning in any class format and a barrier to continued study in the discipline. Promoting representational fluency amongst students who have not excelled in physics prior to university may result in increased retention rates across science-based degree programs as more students have the both the tool-box and way of thinking to participate in this disciplinary context.

Characteristics of representational fluency

Gilbert defined three written modes of representation; verbal, symbolic and visual (2004). By analysing first year student responses by coding them into representational categories, we have been able to link representational fluency to various facets of multi-representational use.

The importance of combining multiple modes

Representationally fluent students used significantly more representations per question than those with low representational fluency. Such students are not reliant on only one mode to make meaning, rather they demonstrate the metacognitive skill of recognising the particular suitability of a range of representations to convey different information for varied purposes. This means that they can not only choose the most appropriate representation for a given situation (Dufresne, 2004), but will combine representations in order to best present their response. This practice of combining multiple modes relies on the ability to translate between representations, an essential element of representational fluency (Bieda & Nathan, 2009; Nistal et al., 2009).

Therefore, representationally fluent students utilise multiple modes of representations in order to make meaning, solve problems and communicate within a scientific discipline.

Gaining proficiency in symbolic and visual modes

Over the whole survey, the students who had low representational fluency had a high dependency on word-based representations. This verbal mode of representations is the written mode most in common with other communities of discourse such as historical or literary studies. In contrast, the visual and symbolic modes are more prevalent in mathematical and scientific disciplines than other contexts. The “authentic” level of representational use (that used by experts) on the RFS involved a high level of symbolic and visual modes, graph-based representations being an example of both modes. In addition to students over-dependence on the verbal mode, qualitative analysis of the RFS supports prior research that physics students do have a preference for the symbolic mode over the visual mode (Meltzer, 2005). This was evident for item III as well as other items on the survey.

Scientific representational fluency therefore involves a proficiency in symbolic and visual modes, in addition to the more universal verbal mode.

The requirement of representational fluency for learning physics

Finally, analysing the responses that students gave through the perspective of representational fluency reveals not only their approach to problem solving but the method by which they integrate new information with prior knowledge (that is, the method by which they learn). Their responses give an indication to the way they use representations to make sense of the world around them. As each representation has different affordances (Gibson, 1977), individuals who can use a wide variety of representations will be more likely to be adept at making meaning from any scientific perspective, not just the particular lens that physicists use to view the world.

The development of scientific representational fluency is essential for successful physics students.

CONCLUSION

Representational fluency has been defined through analysing university physics student responses to the RFS. Representational fluency includes authentically making meaning using combinations of modes of representations including verbal (word-based), visual (diagram and graph based) and symbolic (equation and graph based) representations. The cross-sectional analysis of representational fluency at The University of Sydney revealed that students who were exceptional at high school physics are more likely to exhibit a high representational fluency than other students who had studied the same levels of physics pre-university. This presents a particular challenge to first year physics instruction at tertiary institutions to ensure that students can develop representational fluency in order to participate in the disciplinary discourse.

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APPENDIX

The Representational Fluency Survey (RFS)

http://physics.usyd.edu.au/super/RFS/The%20Representational%20Fluency%20Survey.pdf