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INVESTIGATING COGNITIVE DEMAND OF HIGHER-LEVEL LEAVING CERTIFICATE MATHEMATICS EXAMINATION TASKS PRE- AND POST- CURRICULUM REFORM

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In 2010 the phased introduction of the new Project Maths curriculum began in post-primary schools in Ireland. This new curriculum aimed to enable students to develop problem-solving skills by providing relevant, contextual applications of mathematics, while simultaneously increasing the levels of cognitive demand required of students. This research aims to investigate whether the levels of cognitive demand required to complete tasks in the Leaving Certificate Higher-level mathematics examinations changed as a result of the curriculum reform. The methodology of this research includes the systematic analysis of Leaving Certificate examination tasks, from 2007 to 2017, using an adaptation of the Stein and Smith (1998) task analysis framework. Using this framework, tasks were classified as being of high-level or low-level cognitive demand. Analysis of the data collected suggests that a statistically significant increase in the levels of high-cognitive demand tasks did occur following the curriculum reform. Our findings are discussed in relation to two recent studies that used different frameworks to examine the cognitive demand of tasks in post-primary mathematics.

INTRODUCTION

The Project Maths (PM) reform of the mathematics curriculum in Ireland aimed to provide students with contextual, problem-solving based tasks in order to move the focus away from abstract, procedural mathematics, thus increasing the levels of cognitive demand, or the levels of thinking, required by students. In this study, we aim to analyse the levels of cognitive demand required of students in the Leaving Certificate (LC) Higher-level mathematics examinations before and after the PM reform. The task analysis framework of Stein and Smith (1998) is applied to classify LC mathematics tasks as being of high-level, or low-level, cognitive demand. This study will endeavour to answer the research question: in what ways, if any, were the levels of cognitive demand required in the Leaving Certificate Higher-level mathematics examinations influenced by the Project Maths reform?

LITERATURE REVIEW

Cognitive demand

Cognitive demand can be defined as "the kind and level of thinking required of students in order to successfully engage with and solve the task" (Stein, Smith, Henningsen & Silver, 2016, p. 1). The type of thinking required of the student depends on the nature of a particular task or learning objective (Stein & Smith, 1998) and thus the importance of cognitive demand is seen in its relationship to student learning. While there are a number of frameworks for analysing cognitive demand in the literature, we focus on the work of Stein and Smith (1998) who divide cognitive demand into two levels: low-level and high-level demand. Low-level cognitive demand tasks include: memorisation tasks; and procedural tasks without connections to concepts. High-level cognitive demand tasks include: procedural tasks with connections to the underlying concept; and, tasks that require students to 'do mathematics' in contrast to applying a practiced procedure. Stein and Smith's framework (1998) further includes descriptor-based subcategories of each of these four categories of tasks. (Their framework, which has been adapted for use in this study, is given in Figure 2.)

Analysis of Irish examination papers

In recent years, two studies examining cognitive demand of Irish mathematics examination papers have been carried out. The first study views the contexts, content, and processes underpinning the Junior Certificate (JC) mathematics examinations before and after the PM reform (Cunningham, Close, & Shiel, 2017). The data comprised the JC mathematics examinations from 2003 and 2015 and analysis was conducted using the TIMSS and PISA frameworks (Cunningham et al., 2017). Their findings suggest that there was some movement over time towards placing more emphasis on higher-level cognitive demand tasks in the JC mathematics examinations. However, the study found that this movement was not at a level that would be expected following such a broad reform.

The second study comprised an empirical review of the intellectual skills and knowledge domains in the LC examinations from 2005 to 2010 (Burns, Devitt, McNamara, O'Hara, & Brown, 2018). They used the presence of key words and their context to analyse the levels of cognitive demand in twenty-three LC subjects, including mathematics. The study found that the intellectual skill of 'apply', of low-level cognitive demand, had an occurrence of 90.6% in the mathematics examinations. This finding suggests that a high status is attributed to performance of procedural techniques in the mathematics examinations. The research concluded that the general emphasis on knowledge recollection and lack of emphasis on high-level cognitive demand in the written examinations was detached from the aims of the LC.

Two other studies conducted with the use of Stein and Smith's (1998) framework will be mentioned here. The first study found that LC Higher-level maths papers in 2009 and 2010 contained approximately 25% questions of high-level cognitive demand (Aysel, O'Shea, & Breen, 2011). The second study suggests that further effort is needed to increase the levels of high cognitive demand tasks within Irish LC mathematics textbooks (O'Sullivan, 2017).

METHODOLOGY

Data collection

The LC Higher-Level mathematics papers (paper 1 and paper 2) were collated from the years 2007 to 2017 inclusive. This timeframe was chosen so that there would be an adequate amount of data from before and after the PM reform. Due to the phased introduction of the PM syllabus, additional papers were set between 2010 and 2013. In total, twenty-seven papers were collected and included in the study. From the old syllabus, paper ones were collected from 2007 to 2012 and paper twos were from 2007 to 2011. From the PM syllabus, paper ones were collected from 2012 to 2017 and paper twos from 2010 to 2017. Two paper ones (2011 PM and 2013) contained elements from both the old syllabus and the PM syllabus. In addition to this, the 2013 paper one and 2013 PM paper one had 75% of their questions in common. Therefore, the 2013 paper one was not included in the analysis of the dataset. The paper one examinations contained eight questions prior to the syllabus reform and nine questions following the reform. Regarding paper two, each paper prior to the PM reform contained eleven questions, and nine questions after the reform. However, given the element of choice in paper two prior to the reform, and due to the small proportion of students (5%) attempting questions nine, ten and eleven (SEC, 2005), we included only the first eight questions from these papers in this study. For the purpose of this research, the unit of analysis is part of a question, for example, (a)(i) or (b)(ii). These units of analysis will be referred to as tasks. In total, 1018 tasks were analysed.

Data analysis: framework and procedures

Each task was analysed using an adapted version of Stein and Smith's task analysis framework (1998), seen in Figure 2. Each descriptor within the framework was given a label to identify it within the papers. These labels can be seen in Figure 2. The types of tasks were colour-coded to distinguish them during the coding process. As the task analysis guide was initially designed as a framework for in-class tasks (Stein & Smith, 1998), it was necessary to adapt the framework to ensure it was suitable for examination tasks. For example, while many of the examination tasks could be classified as high-level cognitive demand if it had been the students' first time engaging with those concepts, they were instead classified as low-level cognitive demand because the students' previous experience with those concepts in the classroom was acknowledged.

The tasks in each paper were coded manually by the first author using the framework below. The coding was done with reference to each examination's marking schemes in order to assess the levels of cognitive demand required to receive full marks in each task. Individual tasks were analysed to determine which descriptors depicted the task. Descriptor M1 was applied to every task because every task requires some element of producing previously learned rules or facts. Hence M1 was not included in the analysis. The following is an example of a task and how it was coded:

(c) *A* and *B* are two helicopter landing pads on level ground. *C* is another point on the same level ground. $|BC| = 800$ metres, $|AC| = 900$ metres, and $|\angle BCA| = 60^\circ$.
A helicopter at point *D* is hovering vertically above *A*.
A person at C observes the helicopter to have an angle of elevation of 30°.

(i) Find $|AD|$, in surd form.

(ii) Find $|BD|$.

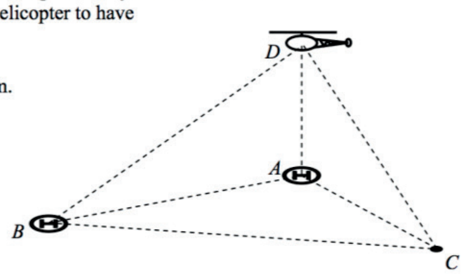

Figure 1: Task taken from 2011, paper two, question (5), part (c)(i).

This task was labelled with descriptors P1, P2, P5 because the use of a procedure to calculate a length in a triangle given such information should be evident to students as a result of their prior experience with previous tasks and would therefore require limited cognitive demand to complete the procedure. The task was also coded with the descriptor PC3 because in order to complete this procedure, students must first make the connection between the worded-representation and the diagrammatic-representation of this task. Some tasks contained descriptors from only one classification hence they were categorised as that type of task.

However, some tasks contained descriptors from multiple classifications. In these cases, the task was classified by the highest level of cognitive demand present. This method of classification was chosen because, while a task may be primarily 'procedures without connections', a connection to the underlying concepts must be made to complete that task, and thus obtain full marks in the examination question. In this particular example, the mathematical procedures required to complete the task were straightforward and could be completed with limited cognitive demand. However, the fact that the students were required to make connections between multiple representations ensured that a higher-level of cognitive demand was needed to complete the task fully. Therefore the task was classified as 'procedures with connections' due to the descriptor with the highest level of cognitive demand present.

Low-Level Cognitive Demands	High-Level Cognitive Demands
Memorisation Tasks **M1**. Involve either producing previously learned facts, rules, formulae, or definitions or committing facts, rules formulae, or definitions to memory. ***This descriptor was automatically assumed to be present in each task because every task requires the production of previous knowledge.*** **M2**. Cannot be solved using procedures because a procedure does not exist or because the time frame in which the task is being completed is too short to use a procedure. **M3**. Are not ambiguous- such tasks involve exact reproduction of previously seen material and what is to be reproduced is clearly and directly stated. **M4**. Have no connection to the concepts or meaning that underlay the facts, rules, formulae, or definitions being learned or reproduced.	***Procedures with Connections Tasks*** **PC1**. Focus students' attention on the use of procedures for the purpose of developing deeper levels of understanding of mathematical concepts and ideas. ***This descriptor was applied if the task highlighted a link to students between procedures and underlying concepts, or if the task required students to notice a concept based on the repeated use of procedures.*** **PC2**. Suggest pathways to follow (explicitly or implicitly) that are broad general procedures that have close connections to underlying conceptual ideas as opposed to narrow algorithms that are opaque with respect to underlying concepts. **PC3**. Usually are represented in multiple ways (e.g. visual diagrams, manipulatives, symbols, problem situations). Making connections among multiple representations helps to develop meaning. ***This descriptor was applied if the task included any additional representations of the initial question.*** **PC4**. Require some degree of cognitive effort. Although general procedures may be followed, they cannot be followed mindlessly. Students need to engage with the conceptual ideas that underlie the procedures in order to successfully complete the task and develop understanding. ***In this descriptor, the idea of not following the procedure mindlessly was focused upon. This descriptor was used if a student was required to use familiar procedures but it was not obvious that the procedure was required from the task or prior experience.***
Procedures without Connections Tasks **P1**. Are algorithmic. Use of the procedure is either specifically called for or its use is evident based on prior instruction, experience, or placement of the task. ***In this descriptor experience was taken to be the students' previous experience of completing fundamentally similar tasks in class or previous exam papers.*** **P2**. Require limited cognitive demand for successful completion. There is little ambiguity about what needs to be done and how to do it. ***In this descriptor it was taken that the lack of ambiguity could come from the fact that the student would have completed many similar questions in class.*** **P3**. Have no connection to the concepts or meaning that underlie the procedure being used. ***This descriptor was used infrequently as very few tasks were completely unrelated to any concept or meaning.*** **P4**. Are focused on producing correct answers rather than developing mathematical understanding. **P5.** Require no explanations or explanations that focus solely on describing the procedure that was used.	***Doing Mathematics Tasks*** **DM1**. Require complex and non-algorithmic thinking (i.e. there is not a predictable, well-rehearsed approach or pathway explicitly suggested by the task, task instructions, or a worked-out example). **DM2.** Require students to explore and to understand the nature of mathematical concepts, processes or relationships. **DM3.** Demand self-monitoring or self-regulation of one's own cognitive processes. **DM4**. Require students to access relevant knowledge in working through the task. ***This descriptor was used when a task contained multiple elements or topics and students were required to use relevant knowledge from a variety of areas in mathematics.*** **DM5**. Require students to analyse the task and actively examine task constraints that may limit possible solution strategies and solutions. **DM6.** Require considerable cognitive effort and may involve some level of anxiety for the student due to the unpredictable nature of the solution process.

Figure 2: Adaptation of Task Analysis Guide cited in Boston and Smith (2009). Descriptors labelled with relevant codes e.g. 'P3'. Adaptations highlighted in bold and *italics.*

A random sample of ten tasks was given to two other mathematics teachers to code. The framework was shared with them and they were asked to use the descriptors to classify the tasks as a particular type. Both teachers matched the first author's classifications for nine out of ten tasks. Once the tasks had all been classified, the number of tasks in each category was counted for every year to assess the levels of cognitive demand required to complete each paper. The proportion of each type of task was compared for every year before and after the PM reform in order to assess if changes to the levels of cognitive demand had occurred. A significance test (two tailed t-test with 95% confidence interval) was then conducted to analyse if the levels of cognitive demand were significantly different as a result of the PM reform.

FINDINGS

Percentage of task-types before and after the PM reform

The percentage of tasks under each of the four task-types in Paper 1 and 2 combined from 2007 to 2017 is given in Figure 3.

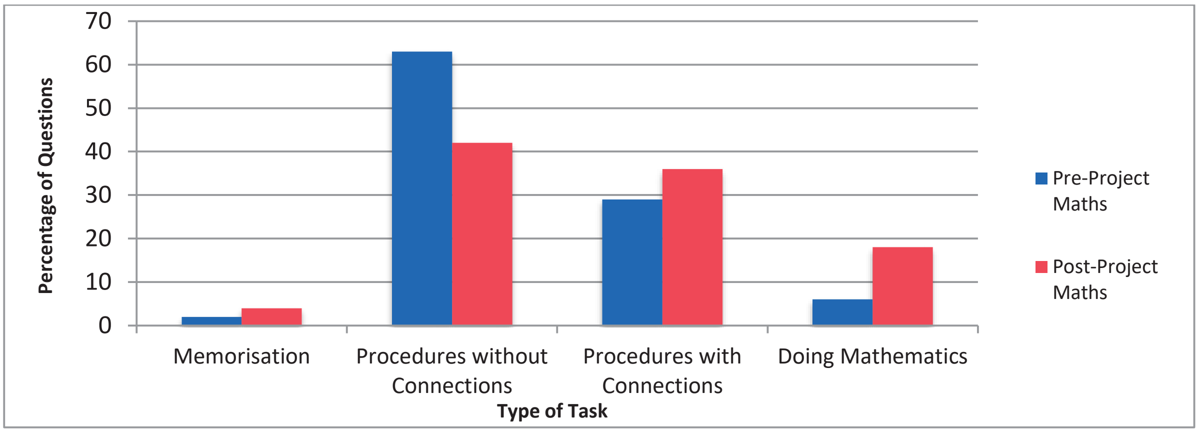

Figure 3: Percentage of tasks under each of the four task-types in Paper 1 and 2 together, before and after the complete PM reform. This data does not contain the 2013 paper one due to a 75% overlap with 2013 PM paper one.

From Figure 3, one can see that the most notable difference between the types of tasks before and after the PM reform is the percentage of 'procedures without connections' tasks. Before the reform the average percentage of 'procedures without connections' tasks was 63%, and this fell to 42% following the reform. This difference was significant within a 95% confidence interval. Another noticeable difference is the increase in high-level cognitive demand tasks ('procedures with connections' and 'doing mathematics') after the reform. This is again significant within a 95% confidence interval.

Distribution of task-types

In Figure 4 and 5 we see the percentage of tasks under each of the four task-types in the paper one and paper two examinations. We notice that in both papers the majority of tasks are procedural, with the papers consisting, on average, of 85% procedural tasks, both 'with connections' and 'without connections'. 'Procedures without connections' emerged as the dominant task type, with papers consisting on average of 52.5% of these tasks. We see in

Figure 4 that in the majority of paper one examinations, the low-level cognitive demand tasks were more frequent than the high-level cognitive demand tasks. As can be seen in Figure 5, the distribution of low-level and high-level cognitive demand tasks is more even across the paper two examinations.

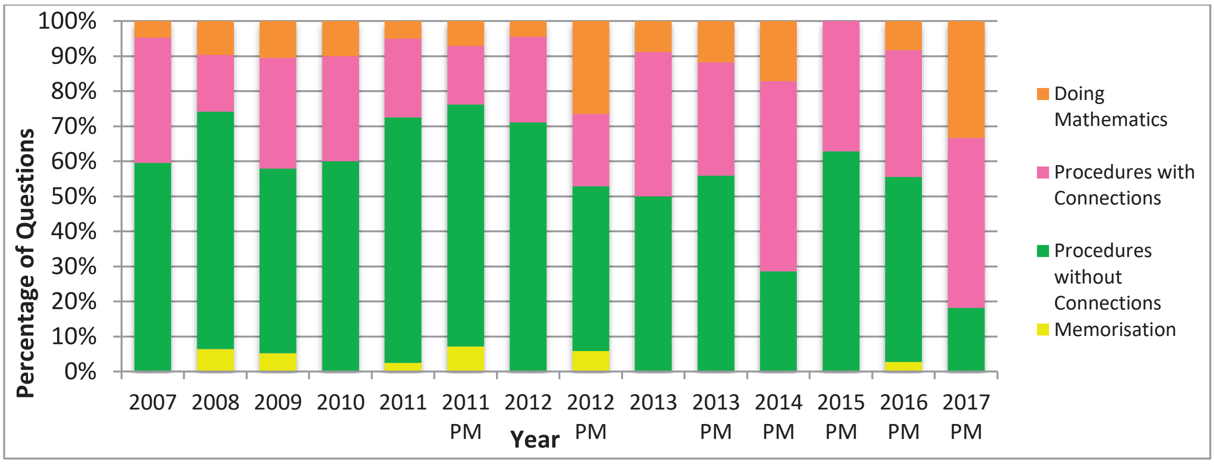

Figure 4: Percentage of tasks under each of the four task-types in LC Higher-level paper one examinations from 2007-2017. Note that 2013 and 2013 PM contained 75% of the questions in common.

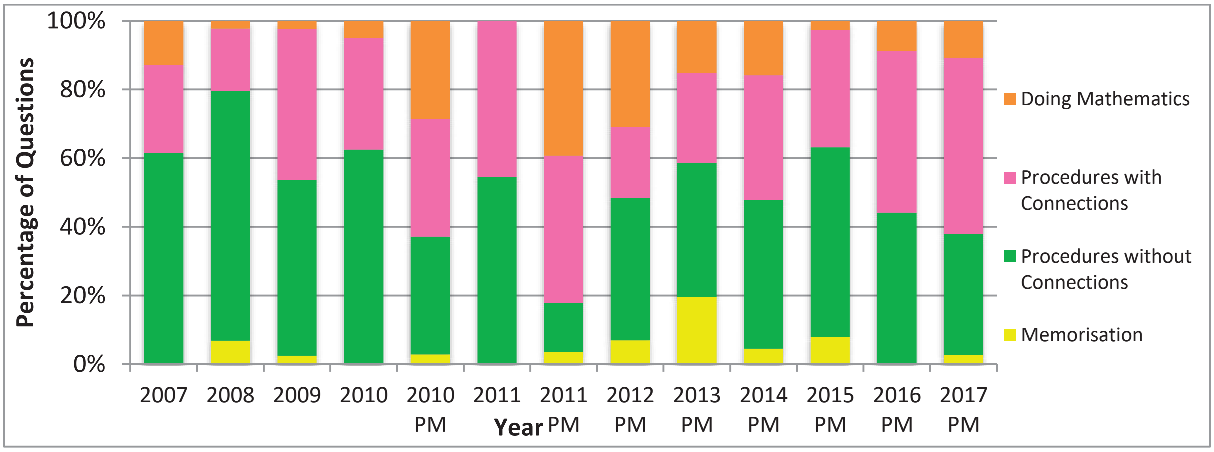

Figure 5: Percentage of tasks under each of the four task-types in LC Higher-level paper two examinations from 2007-2017.

DISCUSSION AND CONCLUSIONS

Consistency with the aims of PM

These results are consistent with the aims of the PM curriculum, which were to increase the levels of cognitive demand by involving students in problem-solving and providing contextual applications of mathematics. The findings show that "procedures without connections" tasks was the dominant task-type, both before and after PM. This may be explained by the number of tasks within pre- and post-PM syllabi that are procedure based, such as solving a quadratic equation or differentiating a function. It is necessary for these topics to be assessed within the examination as they form a core part of the syllabus. It is also important to note, that many of these tasks are considered as 'procedures without connections' because of the prior experience students had with these procedures when engaging with them in class. These procedures can require high-levels of cognitive demand during the initial knowledge acquisition phase, with the levels of cognitive demand decreasing as students gain experience practicing these procedures.

The increase in ‘doing mathematics’ tasks reflects the aim of PM to increase the levels of problem solving required of students and decrease the levels of abstract, practiced procedures. However, while providing ample opportunities for students to ‘do mathematics’ in the classroom can provide challenging and rewarding learning experiences, it could be argued that by the time the students attempt their examinations, the majority of the ‘doing mathematics’ tasks should be complete. It may be more appropriate that students have the opportunity to apply the knowledge they have mastered in a summative assessment situation.

Topics relating to task-types

Following a brief review of the topics on each paper and the task-types with which they were classified, it was found that the proportion of task-types per paper can often be linked to the types of topics that paper assesses. For example, the ‘memorisation’ tasks appeared most frequently in paper two examinations. A reason for this could be the regularity with which the topic of geometry appears in paper two. Many of the tasks classified as ‘memorisation’, were those that asked students to reproduce a proof from the geometry strand.

As previously discussed, the PM reform aimed to provide relevant contextual applications of mathematics for students. In many cases, these applications appeared in the form of a word-problem with corresponding diagram, requiring students to make a connection between multiple representations of a concept. In such cases, the tasks required students to complete straightforward, practiced procedures, and so would initially be classified as ‘procedures without connections’. However, the addition of the diagram ensured that students were required to make connections between representations, resulting in them being classified as ‘procedures with connections’.

Comparison of marks awarded per task-type

One question that arose from this research was whether or not the PM reform would place a higher value on cognitively demanding tasks in examinations, thus awarding them higher marks than lower cognitively demanding tasks. When comparing the percentage of marks available to the percentage frequency of each task-type in the 2007 and 2017 examinations, it was found that these percentages were approximately even. While the overall levels of cognitively demanding tasks increased, these tasks were not awarded a disproportionate amount of marks.

Comparison of findings with current Irish research

When analysing the results of this study in relation to comparable Irish studies, similarities occur in the findings. Our findings correspond with those of Cunningham et al. (2017) who also found increased levels of cognitive demand, albeit in the JC mathematics examinations, after the PM reform. In the empirical review of the LC mathematics papers from 2005 to 2010, Burns et al. (2018) found that 97.5% of tasks investigated were procedural. This study found that prior to the PM reform (2007-2012), procedural tasks comprised 92% of the examination papers. These results are comparable to the results of the Burns et al. study, strengthening the validity of these findings.

In conclusion, this research has suggested that the aims of the PM reform to increase levels of cognitive demand are being met in relation to the LC Higher-level examination papers. While this should be seen as a positive result, the suitability of having more ‘doing mathematics’ tasks in the examinations must be considered. Asking students to engage in complex and non-algorithmic thinking with an unpredictable solution process under the constraints of time-limitations has the potential to cause anxiety and stress for students in an already highly pressurised situation. While decreasing the levels of ‘procedures without connections’ tasks can be seen as a positive outcome, a corresponding increase in ‘procedures with connections’ rather than ‘doing mathematics’ tasks may be a fairer substitution for examination students.

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