Should the third Newton’s law be the first one? A TLS on dynamics for upper secondary school

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Abstract. In this paper we are presenting the design and evaluation process of a Teaching Learning Sequence (TLS) following Design Based Research (DBR) methodology. The TLS was designed for the upper secondary school students on particle dynamics. In this work, we present the very first results of the process. The iterative DBR methodology is presented giving evidences about design decision and tools for evaluation. This TLS was implemented in a post compulsory high school in the Basque Country. The results obtained in the first implementation show that there are improvements in the learning achieved by students in comparison with a control group. The strengths and weaknesses of the TLS will be analyzed for future redesign phase into DBR phases.

1. Introduction

Dynamics, probably, is the most popular topic in physics, particularly in secondary and high school. There are plenty of research works on students’ difficulties in Dynamics and the difficulties are very well established due to very well known questionnaires like Force Concept Inventory (FCI) [1]. Although there are also some proposals for implementation with the aim to overcome those difficulties most of these proposals do not make explicit the design decisions and the evaluation of the proposal is usually done only looking to the students’ results, leaving at the side the evaluation of the quality of the sequence. In this work, we are going to describe the design and evaluation process of a Teaching Learning Sequence (TLS) following Design Based Research (DBR) methodology [2, 3].

The principal aim of the TLS we are presenting in this work is to give students a learning path to follow to achieve a conceptual understanding on Newton’s Laws and dynamics. With this purpose the present TLS would like to be “both an interventional research activity and a product, like a traditional curriculum unit package, which includes well-researched teaching-learning activities empirically adapted to student reasoning” [4].

To design the TLS we choose DBR methodology. This methodology allows us to integrate theoretical principles in the design process at the time that we can make explicit the design and evaluation decisions [2, 3]. This methodology proposes to follow three general steps; design phase, the teaching experiment and the analysis and evaluation of the teaching experiment and finally, a redesign phase. Although DBR methodology does not propose any commitments in relation to the nature of learning or teaching strategies, is expected the articulation of those commitments in the decision making process.

In this paper we are going to start answering the following research question. To what extent does the DBR methodology improve the design, evaluation and refinement of the TLS in the case of Newton's laws in high school students?
We are going to define the context for the TLS and define the learning objectives based on an epistemological analysis. On the other hand, we are going to define students’ learning difficulties based on well established previous works [1] to define the Learning Demands [5] and do explicit the design choices and show that the design decision are research informed.

2. Designing a TLS on dynamics following DBR methodology

2.1. DBR Methodology

We chose DBR methodology to a) Design, b) implement and c) evaluate the TLS on dynamics for high school [3]. In this section, we present, how we develop each phase and which kind of information and tools do we use to do so. It is necessary to mention that the presented phases are not “carried out in a linear way but in an iterative way” [3], and so, we are going to explain how the phases are related in the process.

From all the research informed elements we have included in the design of the TLS, there are some of them that are crucial for the success of the process: the context where the TLS is going to be implemented, the definition and use of the design tools [6, 7] and the link with the specific tasks that are going to guide the learning trajectory [8].

In design phase, the clear definition of the learning objectives is crucial if we want to test the achieved learning and use these results for a future redesign of the TLS. In this section we will propose a first version of a TLS to implement in the teaching experiment. To define the learning objectives an epistemological analysis is needed to foster define the Learning Demands taking into account the students’ difficulties and the teachers’ previous experience teaching dynamics. So it is very important to inform teachers who are going to implement the TLS about the theoretical frames and research results as part of the PCK (Pedagogical Content Knowledge). Table 1 shows the scheme of the design phase.

| Contextual elements and epistemological analysis of school curriculum content | Students ideas and reasoning of School curriculum content | Interactive environments for understanding based on skills and attitudes for scientific research |
|---|---|---|
| **Learning objectives** | **Learning difficulties and Learning demands** | **Teaching strategies** |
| Building the driving problems that lead to proposed learning trajectory | TLS activities | Teacher’s guide for implementing the TLS |

The implementation phase happens when the designed material is administered to students in the classroom and the evaluation phase implies an iterative process where several tools are used. In our proposal in table 2, the design decisions of the TLS are validated empirically in two dimensions [9].

First we measure the quality of the sequence that means that we look if there are difficulties a1) in the implementation regarding to the comprehension of the activities, wording, graphs, pictures… a2) in relation with the scheduled time and a3) regarding to innovative proposals. In relation with the second dimension, we measure the learning achieved by students that follow the TLS regarding to b1) concepts, models and theories and b2) and scientific skills in the comprehension of the proposed questions relating them with the learning objectives and problem solving strategies.

An essential part of the TLS is the “teachers’ guide” that accompanies the sequence of activities for students. It is important to note that it is usual that teachers make changes in the teaching materials they get and sometimes it is really needed to fit the TLS in the reality of each school. Although the changes are needed, sometimes these changes affect the learning objectives of the TLS and problems arise in evaluation phase and in the learning achieved by students [10]. Furthermore, despite teachers show positive attitude regarding to research based innovative proposals, they are reticence in changes practices.
if new materials don’t give practical solutions to their classroom problems [11]. Taking into account all mentioned above, the teachers’ guides must include a description of scientific content and procedures required to implement the TLS, a detailed description of the learning objectives, teaching strategies and the relation of key activities to achieve the learning objectives [12].

Table 2. Evaluation tools used iteratively during the implementation and redesign of the TLS

| Instruments to detect the quality of the TLS (interpretation difficulties) | Instruments to measure the learning achieved through the implementation of the TLS | Redesign of the TLS |
|---|---|---|
| a.- Teacher’s diary | - Questionnaires on concept and theory understanding | - Restatement of writing issues, analogies, approach, … |
| b.- Student’s workbook | - Problem-based tests on the learning of laws and the acquisition of scientific skills | - Redesign of the activities’ sequence, the sequence and its activities |
| c.- External observers reports | | - Redesign of the pre-requisites of the sequence and its activities |
| | | - Format changes (worksheets, clicks, group work documents, …) |

2.2. The design of the TLS on dynamics

In this section, we are going to apply the tools described in table 1 and show how we make research informed design decisions. We first are going to use the epistemological analysis to define learning indicators. Then, though the application of Learning Demands tool, we will decide how deep do we need to go (how many activities, which teaching strategy, …) to help student in the achievement of each learning objective. Finally we will design the learning path guided by driving problems and the activities.

2.2.1. The context. The TLS on dynamics is going to be designed to be implemented in the first year after compulsory secondary school (16-17) in the Basque Country (Spain). The students attending the course have chosen physics as subject. They have some previous knowledge on kinematics and dynamics from secondary school. In this first implementation we will go into a 29 students group.

Table 3. Relation between epistemological key concepts and learning objectives

| Elements of epistemology | Learning objectives |
|---|---|
| K1, K2 and K3 | i1. Draw free body diagram: |
| | • Chose a frame of reference |
| | • Identify forces |
| | • Identify the body where the force is applied |
| K4 and K5 | i2. Apply in a correct way the law’s of dynamics |
| | i3. Develop problem solving skills |

2.2.2. Epistemological analysis and learning objectives. The epistemology of physics on dynamics draws out a starting point from only some primitive elements and showing how they could evolve into a complex system of reasoning. When the concept of force is defined, the first characteristic of the theory of physics mention is that it is an interaction. The concept interaction itself, involves that there must be two bodies implied in and so, in both bodies is going to detect that interaction between them. This characteristic of the force is the Newton’s third law. Other characteristic of the force is that the net force acting on a body accelerates that body proportionally to the force [13, 14, 15]. The relation between the force and the
acceleration is defined as the inertial mass of the body. The total acceleration of a body could have two
components, tangential acceleration that changes the speed and normal acceleration that changes the
direction of the velocity. In our analysis each new element have been defined in terms of pre-existing
elements, and once introduced, they are used with a fixed meaning. They are intended to point towards what
an appropriate formal language may be required to do. We will present in the presentation the defined
objectives for the TLS.

Based on this analysis, we define the key ideas for understanding the concept of force and Newton’s
laws:

K1. To identify the source of force and to understand that it is an interaction between two bodies.
K2. To identify the force as a vectorial quantity.
K3. To understand Newton’s 3rd law and to identify action-reaction forces appear always in different
bodies.
K4. To understand and to apply Newton’s 2nd law and relate force and acceleration.
K5. To understand and to apply Newton’s 2nd law to dynamics of the rotational motion.

And based on these key ideas about force and Newton’s Laws and the curriculum of physics for high
school, we define the learning objectives for our TLS in table 3.

The defined key ideas are essential to define the learning objectives of the TLS. Thus, the learning
objectives are based not in the curriculum or in the tradition of how physics is taught but in the arguments
informed by the epistemology of physics.

2.2.3. Learning difficulties and learning demands. The learning difficulties related with dynamics are
researched in deep and they are very well established thanks to questionnaires as Force Concept Inventory
[1]. The literature shows that most relevant students difficulties in relation with our learning objectives are:
a) Students have misunderstanding interpreting the graphs and when to work with vectors; b) some students
understand the force as an “impetus” that disappears over time; c) students think that objects with big mass
can apply bigger forces and only active objects exert force; d) regarding forces and motion: The last force
acting defines movement of the body, Force and speed are proportional and friction forces stop bodies.

Table 4. The result of the application of the tool learning demand confronting students’ difficulties
and leaning objectives of the TLS.

| Difficulty | Learning objectives | Learning demand |
|------------|---------------------|-----------------|
| D1. To understand graphs | i3 | High |
| D2. To work with vector magnitudes | i1 | High |
| D3. The idea of Impetus | i2 | High |
| D4. Only active objects exert force | i1, i2 | Low |
| D5. Bigger mass objects exert bigger forces | i1, i2 | Medium |
| D6. Friction forces make bodies stop | i1, i2 | High |
| D7. The last force exerted dominates the motion of the body | i2 | Low |
| D8. Force and velocity are proportional | i2 | High |

Taking into account that the tool learning demand is to identity the ontological and epistemic differences
between students’ known previous knowledge and the science content to be learned, to define them it is
necessary to compare the characteristics of the concepts or law you need to teach and the difficulties
that students show when they start learning those [5]. Thus, in table 4 we compare the students’ learning
difficulties and the defined learning objectives to inform the TLS design phase on the students learning
demands to later on decide about the structure of the activities to be designed.
2.2.4. Design of the learning path, learning strategies and activities. Next step in design phase is related with the learning path. We found four interesting driving problems to guide students through the dynamics:
   I) Looking around everything is at rest. Are there forces on stationary bodies? What is force?
   II) How could we compute the force on bodies at rest?
   III) Is it possible to move a body if total forces acting on the body is zero? What is the relation between the force exerted on the body and its motion?
   IV) How could we compute the acceleration of a body?

| Driving problem | Learning indicators | Strategies to foster learning | Activities (with comments for implementation) |
|-----------------|---------------------|------------------------------|-----------------------------------------------|
| Regarding around everything is at rest. Are there forces on stationary bodies? What is force? | i.1 (K1,K2,K3) | 0. Activation questions. | 1. What is force? (Activities to arise pre/mis-conceptions) |
| Draw free body diagram | Understand the force as an interaction between two bodies | A1. Identify different kinds of force |
| A2. Force is an interaction | A3. No matter the kind of force, it is always interaction |
| A4. Force is interaction, Newton’s 3rd law | A5. Force concept |

In this work we are going to present in detail the part of the TLS related to the first driving problem. We can see the structure of the TLS for this first task in table 5.

2.3. The implementation and evaluation of the TLS
The TLS was implemented in a high school in the in Basque Country with 29 students (16-17 years old) who have chosen physics as topic. They have some previous physics knowledge on kinematics and dynamics from secondary school. There is also a control group of 23 students involved in the research.

Taking into account that the work presented in this work is a project that aims to get a product, the design of the TLS, the evaluation and the redesign have to be based on empirical data obtained during the implementation. It is necessary to analyze empirically the first version of the TLS through the evaluation of the knowledge achieved by the students. The conclusions of this evaluation are going to be taken into account in the redesign.

Following the comments of the table 2 regarding to the first dimension (the quality of the TLS) tools as “Teacher’s diary”, the “external observers report” and “students’ workbook” were analyzed. “Teacher’s diary” is the tools that teachers use to communicate with the researchers during the implementation of the TLS. According to Carr and Kemmis [16], this diary helps teachers to understand better what is happening in their classes. This tool is particularly useful when teachers describe “practical problems” when applying each activity [17]. The “external observer report” is the document where a researcher part of the designers of the TLS, writes the comments during some implementation sessions. With reference to the second dimension, open ended questionnaires are designed to measure the knowledge of students. These questions are designed aligned with the learning objectives, pre and post tests to give control and experimental groups and the analysis of these questions was done following phenomenography [18]. The analysis of each question was made in several iterative cycles by different researchers and the reliability of the categorization measured by Cohen’s kappa.
After analyzing the data, the detected problems are classified into metacognitive difficulties, learning difficulties related to the comprehension and/or interpretation of the activities or learning difficulties related to conceptual understanding. Regarding to these problems modifications in the activities are introduced and/or in activity sequence.

We would like to show an example of a question designed to test the knowledge related with the first learning objective (i1: Draw free body diagram). In the figure 1, we can see the question 1 in pre and post test version. The categorization and the analysis of the question are shown in table 6. The Hake gain [19] in Q1 after the implementation of the TLS is 0.3 and two tailed Fisher test [20] says that there are statistical significant differences between experimental and control groups (\(p=6 \cdot 10^{-18}\)).

![A rabbit is running and jumping. In the figure we can see a moment of the jump. Draw the free body diagram on the rabbit? Explain your drawing](image)

**Figure 1.** Q1 designed to test learning objective i1) in pre test and post test version

| Category                              | Pre (%) | Post (%) | Control (%) |
|---------------------------------------|---------|----------|-------------|
| A Forces are identified and drawn. The drawing is explained | 34.6    | 53.6     | 17.4        |
| B Don’t explain correctly gravitational force | 24.1    | 0        | 0           |
| C Confusion between mass, weigh and gravitational force | 6.9     | 3.6      | 8.7         |
| D Extra forces upwards                 | 27.5    | 35.9     | 52.1        |
| E No answer/so sense                   | 6.9     | 7.1      | 21.7        |

\[\kappa_{\text{pre}} = 0.81 / \kappa_{\text{post}} = 0.88\]

3. Conclusions
The design example we have presented in this document is largely based on previous existing proposals, but we have focused on exemplifying the use of a DBR methodology that we suggest could be used as a general methodological framework for different areas of knowledge. Regarding the research question, the results suggest that using DBR as a methodology to design, implement and evaluate a TLS may be useful for improving the design and redesign of the TLS. In addition, this study provides the community of teachers and designers with a plausible proposal for a common methodology for the design, implementation and evaluation of the TLS that can facilitate comparing different TLS materials. We believe that the overall implementation of a systematic evaluation of TLS would provide designers empirically grounded solutions to use during the design of future TLS. This process of building on known solutions to common problems would help determine which TLS is most efficient for a given issue in a given context, as well as better determine the difficulties still to be resolved.

In this paper, we have faced the problem of the relationship between the evaluation of TLS and its iterative design. Through our general design proposal following the DBR and presenting specific examples of our research, we have demonstrated how our TLS was designed and evaluated and how this evaluation was used in the iterative design process. We do not consider the TLS as an integral solution for scientific education. We have deliberately limited our design proposals to elements with sufficient research support to be accepted into the community as common design elements. These elements constitute the design tools that will be included in a DBR methodology for the design of materials, which will not be equivalent, by themselves, to a complete TLS. The final result will require making contextual decisions both regarding the use of design tools and the implementation of the resulting TLS, understood as specific examples of a more generic TLS for a particular topic.
In summary, in this paper we have developed a way to use DBR as a methodology for the design of a TLS and we have provided an example developed following this methodology with a particular focus on its design and evaluation. We do not suggest that this is a unique result, but we hope it will be a fruitful contribution to change what is now a significant area of research, but to disperse in a research program that may constitute a central component of the field of Science Education.

4. References

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