Applying the 4C/ID-Model to Help Students Structure Their Knowledge System When Learning the Concept of Force in Technology

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Learning in technology education often involves students being confronted with the learning of complex concepts. However, how teaching interventions can be designed to help them learn these concepts better and avoid compartmentalised thinking remain unclear in the literature. This paper presents results from the implementation of a whole-task approach based on a four-component instructional design (4C/ID) model. The intervention focussed on teaching the concept of force and was introduced using interactive and CAD simulations. A protocol analysis was conducted to examine the dynamics of student learning through an experimental intervention that was organised into two task classes of six activities that first aimed to help students (N = 5, grade 12) construct the knowledge elements of different kinds of force, and second to elaborate connections between these elements. We finally measured student achievement using a mechanics inventory, and a factor analysis was conducted based on students' responses to investigate the dynamics of their knowledge system. The primary exploratory results showed that the research intervention, in line with the whole-task approach, was helpful since it offered a time-efficient learning experience to students with low-to-moderate effects on learning progression. It is therefore suggested to teachers that elaborating different meanings of a concept through a whole-task-based approach would be more beneficial to students. Nevertheless, such an intervention would need to last for a longer duration to permit students to better reinforce their learning strategies in managing misconceptions and to stabilise their knowledge system. Some implications in technology education are also discussed.

Keywords: force concept; technology; 4C/ID-model; learning progression; conceptual understandings

Introduction

The research reported in this paper explored the effects of a teaching approach based on an instructional design model aiming to help students improve their knowledge system. Research in conceptual change has been examining intuitive student understandings of concepts (usually known as misconceptions) for decades. Most of these studies were performed in the field of science education where there is a vast number of investigations. Technology education presents different but converging perspectives on students' knowledge acquisition. In the literature, different theoretical frameworks have been describing the learning dynamics of some intuitive concepts.

Examining students' understanding from a complex knowledge system perspective

Many theoretical frameworks have been defined to describe misconceptions and knowledge organisation when learning scientific and technological concepts (Vosniadou, 2013). Among these, a framework theory approach of conceptual change (Vosniadou, 1994) posits students' ideas as being based on strong pre-instructional beliefs about the physical world organised in framework theories. A Knowledge-in-Pieces perspective assumed that students' ideas are fragmented and inarticulate explanatory primitives (p-prims), which are highly context-sensitive (diSessa, 1993). From a complex knowledge system perspective, learning is a complex and dynamic process (Brown & Hammer, 2008). The approaches described above converge in a complex system perspective. For instance, diSessa (2018) described p-prims as complex and dynamic structures since they can be activated and deactivated in specific contexts. Lawson et al. (2019)

defined learners' belief systems as constantly evolving knowledge structures that cover a domain of knowledge. These convergences are reinforced by recent neuroscience developments that showed a coexistence of both students' intuitive ideas and scientific explanations (e.g. Brault Foisy et al., 2015). The complex system perspective involves many properties: dynamic, inconsistency, and variability, but also instability since most students' misconceptions are usually untroubled by instructions (Clement, 1982). This emphasises the need for a more global educational method able to support student learning. Indeed, instructions that can address a mixed student epistemology (Kalman & Lattery, 2018) and give a broader view of a concept are then of utmost importance in the learning process.

Instructional design and knowledge construction in technology education

Recent research in technology education strongly focusses on the importance of concepts and contexts in technology (Rossouw et al., 2011). According to Simondon (2017), concept learning in technology education is defined through actions and activities that are determined by the associated milieu and context in which learners act and resolve technical issues. The knowledge construction therefore suggests that learners should think, understand, and use a technical language and practice (Ginestié, 2017). Educational interventions need to emphasise the integration of knowledge, skills, and attitude in a high level of coordination.

While there is a consensus about the learning dynamics, which is characterised by inconsistency, evolution, and interactivity between knowledge structures, some researchers suggest instructional models that deal with such complexities. Traditionally, most learning instructions are used to fragment concepts into parts, to a level which can be easily learnt. This atomistic approach presents some limitations. In contrast, an holistic approach in instructional research suggests dealing with complexity without losing sight of knowledge interactions and separation (van Merriënboer & Kirschner, 2017). Students may develop compartmentalised thinking on a concept since it is taught differently in different subject areas. A systemic approach of learning should then consider concepts as interdisciplinary so that students are able to develop a broader view of the whole concept. This is highly valuable in engineering and technology education (Rossouw et al., 2011). Interestingly, the approach of a systemic concept can fruitfully combine different subjects.

The 4C/ID-model

The *four-component instructional design* (4C/ID) model (van Merriënboer & Kirschner, 2017) is one of these many instructional models. It aims to deal with complexity using whole-task learning. It has been designed based on the Sweller cognitive load theory (Sweller et al., 2011) and the Mayer's theory of multimedia learning (Mayer, 2014). Cognitive load theory (Sweller et al., 2019) explains how the information processing induced by learning tasks can affect student ability to process new information and to construct knowledge in their long-term memories. When based on the 4C/ID model, an educational intervention introduces four interrelating blueprint components: (1) learning tasks, (2) supportive information (the theory), (3) procedural information (the 'how to'), and (4) part-task practice (van Merriënboer & Kirschner, 2017).

The first component (learning tasks) is the backbone of the model. It is a design based on a real-life, professional situation or in a simulated environment (the principle of authenticity). In a task class, learning should also be varying contexts and conditions to ease transfer (principle of variability) (Paas & van Merriënboer, 1994). The learning is defined with decreasing guidance through a scaffolding process. The second component (supportive information) is the theory that defines and structures the subject domain. It facilitates schema construction and is available during learning. The third component (procedural information) is presented only when needed, namely when students are performing a specific procedure.

Over time, learners should develop automaticity on routine aspects in order to construct strong schemata. The related cognitive process is called knowledge compilation. This automaticity is developed through additional practices (called part-tasks) which is the fourth component.

The 4C/ID model deals with three main issues: fragmentation, compartmentalisation, and the transfer paradox (van Merriënboer & Kirschner, 2017). For example, in learning a concept such as force, both contact and distance force are first identified and learnt in a same task class in different contexts where students can coordinate their learning (diSessa & Wagner, 2005). As shown earlier, this emphasises the interdependence of knowledge structures about the different forces.

Students' learning about force in technology

The focus on the concept of force in this study follows a well-known issue in science about which many debates have developed between scientists (Coelho, 2010) and more recently between technologists (Jouin, 2002). Force is a core concept in physics. It is also considered to be the fundamental concept of mechanics in technology (*ibid*.). According to Jouin (2002), an important property of force lies in its transmissibility at the level of mechanical bonding. However, most students' misconceptions about force have been best described in science (Goris & Dyrenfurth, 2012). Misconceptions can be Aristotelian, Galilean, Newtonian, and so on. We believe that students developed similar intuitive ideas in technology since there is an emphasis on science concepts. However, researchers suggest that technology has its own knowledge that is different from science (de Vries, 2005). Technology usually investigates misconceptions as a process (Goris & Dyrenfurth, 2012). Experts consider design, systems, and modelling as core concepts for engineering and technology education (Rossouw et al., 2011).

The present study

This research investigated the effects of a learning progression based on the 4C/ID-model in complex learning. It aimed to help students elaborate a well-structured knowledge system when learning the force concept in technology. Among the types of learning tasks, the intervention first introduced interactive simulations as worked examples. The aim for students was to familiarise themselves earlier with – and have a broader view about – the different forces and mechanical principles involved. The teacher was asked to engage in deeper discussions on each situation with students when needed.

Method

Participants

The study was conducted in a French technological high school located in the south of France. A student group from grade 12 (N = 28, *mean age* = 17.28) participated in the study. However, only five students (one group of three and a second of two) were specifically followed in the class during their apprenticeships. This sampling allowed the researcher to follow in-depth the evolution profile of these students and to ensure the necessary data collection, thus helping to assess the student learning as well as the teaching intervention. These five students were then interviewed after the intervention.

Procedure

We administered the force concept inventory (FCI) (Hestenes et al., 1992) as a pre-test to measure students' understanding. The designed intervention was then performed with all students. It was organised into two task classes of three activities each (Table 1). The first task class aimed to construct knowledge elements regarding two kinds of force: contact force (normal, friction, elastic/tension) and distant force (gravitational), and a specific mechanical interaction called torque. The second task class helped students create links between these elements. The activities also included internal forces, stresses, strains, and displacements caused by both contact and distant forces. The progression has been described in Table 1 below. The intervention was concluded with a post-test using a mechanic baseline test (MBT) (Hestenes & Wells, 1992) to measure students' problem solving skills. Moreover, a micro genetic learning analysis through clinical interviews (diSessa, 2017; Parnafes & diSessa, 2013) was conducted with the students who were being followed to investigate their knowledge systems regarding the concept of force.

Table 1. Designing learning activities.

Task class 1	**Task class 2**
TA11. Gravity and Friction Forces	***TA21. Contact and Elastic Forces***
Technical artefact: Projectile motion	Technical artefact: Rocker arm mechanism
Context: Launching a water rocket in an interactive simulation environment	Context: Internal combustion engine of an automobile. CAD Structural Analysis
TA12. Torque by Contact Forces	***TA22. Internal Forces and Stresses***
Technical artefact: Beetle on a rotating plate	Technical artefact: CAD model of a bike frame
Context: Interactive simulation environment	Context: CAD Structural Analysis
TA13. Contact Forces and Gravity	***TA23. Contact, Distant Forces, and Torque***
Technical artefact: A box	Technical artefact: Robot and load
Context: Pulling and pushing a load in an interactive simulation environment	Context: robot functioning

Data analyses

Data has been collected. These were students' scores, written and numeric documents, dialogues and screenshots recordings. Both quantitative and qualitative methods have been used to analyse these data and helped to track the profile of each student. The quantitative data from the MBT were analysed using two approaches: factor analysis and non-parametric item response theory (NIRT) analysis since the normality assumptions ($p < .05$) were not met (The NIRT analysis is not reported here). Interactions (vocal recordings and interviews) were transcribed and analysed globally using a multi-dimensional framework (Leander & Brown, 1999) consisting of six aspects: focal, conceptual, discursive–symbolic, institutional, social, and affective.

Statistical analyses

An exploratory factor analysis (EFA) was first conducted with students' responses to the MBT using R software with the psych package to analyse the underlying factors in student knowledge structures when learning about force. Bartlett's test indicated a correlation adequacy, $X^2(300) = 374.87$ $p = .002 < .05$ but the KMO (Kaiser–Meyer–Olkin) test indicated a poor sampling adequacy of MSA = .23 ($N = 28$). A parallel analysis suggested three overall factors and a three-factor model was tested. Principal factor analysis estimation was used with oblimin rotation because of expected factor correlation. After testing all 26 items from the MBT (excluding item5 due to missing value error), three items (item2, item21, and item25) were split across several factors using the criterion that loadings must be greater than .30. These items were removed from further analysis. A final three-factor model was tested, and the factor loadings are presented in Table 2. This model achieved simple structure. It had poor fit regarding the RMSEA (0.155 with 90% confidence intervals null) and the RMSR (.12 > .05). However, these indicators are strongly affected by sample size (N should be > 200). To resolve this issue, a Tucker Lewis Index (Bentler & Bonett, 1980) was calculated which had a good fit at 1.822 > 0.90. Additionally, the CFI index, which is less affected by sample size (Hu & Bentler, 1999) indicated an acceptable value at .77.

Results

The analyses of quantitative data on students' performances showed that students' skills had improved through instructions. As illustrated by the factor loadings (Table 2), moderate but positive relations were elaborated between force, energy conservation, and acceleration. Factors confirmed moderate positive effects in student knowledge. The reliability of factors was moderate with .57, .41 and .71 for factors 1, 2, and 3 respectively. The mean scores for each factor were: Factor 1 $M = 0.18$ ($SD = 0.25$), Factor 2 $M = 0.51$ ($SD = 0.23$) and Factor 3 $M = 0.12$ ($SD = 0.29$). Factor 1 examined students' knowledge of force, energy, and Newton's second law. The study suggested the impact of force as one cause of acceleration and an influence on the energy conservation as a first factor model. It showed the presence of positive relations in students' knowledge structures when linking the different (distant and contact) forces (Items 6–9) to Newton's second law (Item17) as well as their impact on the conservation of mechanical energy (Item10). Factor 2 suggested links between students' knowledge about acceleration and the Work–Energy principle. It confirmed relationships in student learning between knowledge about acceleration (Items 1 to 4), and between these items and the Work-Energy principle (Item20). Finally, Factor 3 underlined students' knowledge about acceleration (Item23) and the impulse–momentum notion (Item16).

Table 2. Three-factor (F) Model Loadings.

Items*		**F1**	**F2**	**F3**
1	Linear motion: constant acceleration, object velocity	-0.11	**0.66**	0.13
3	Linear motion: constant acceleration, net force vs time	0.07	**0.44**	0.19
4	Curvilinear motion: tangential acceleration	0.23	**0.46**	-0.28
20	Work-Energy principle (kinetic energy through pucks)	0.14	**0.33**	-0.29
6	Gravitational free-fall (a frictionless ramp example)	**0.63**	-0.07	0.12
9	Friction and second Newton's second Law	**0.49**	-0.42	0.01
10	Energy conservation (playground slide example)	**0.39**	0.20	0.15
17	Second Law: dependence on mass	**0.51**	0.01	0.13
16	Impulse-Momentum: direction of an impulse	0.02	-0.09	**0.82**
23	Linear motion: average acceleration	-0.04	0.26	**0.65**
7	Superposition principle (pulling of a block)	0.24	0.07	-0.12
8	Curvilinear motion and second Law	-0.28	-0.05	-0.20
11	Energy conservation (swinging system)	-0.34	0.01	-0.13
12	Curvilinear motion and Newton's third Law	0.12	-0.07	0.29
13	Third Law and superposition principle	-0.02	-0.69	0.06
14	Third Law (forces exerted by the rope of an elevator)	-0.02	-0.18	0.03
15	Momentum conservation: direction of the change in momentum	-0.74	-0.05	0.15
18	Linear motion and second Law	-0.12	0.25	-0.14
19	Superposition principle (a hockey puck example)	0.22	-0.10	-0.12
22	Impulse-Momentum: momentum comparison	-0.24	-0.13	-0.07
24	Linear motion: integrated displacement	0.26	0.13	0.25
26	Gravitational free-fall	0.07	0.18	-0.21

*The full description of the MBT items can be found here: https://www.physport.org/assessments/

After the intervention, the researcher conducted a micro genetic analysis (Parnafes and diSessa, 2013). A 30-minute discussion with each of the 5 students, enabled the rapid categorisation of the dynamics of their knowledge systems using multi-dimensional aspects of learning interactions: focal and conceptual, discursive-symbolic and institutional, social, and affective (Leander & Brown, 1999). These results are not reported here but will be discussed as part of the PATT conference.

Discussion, limitations, and implications

The implications of the whole-task approach, interactive and CAD simulations, pair and group discussions, as well as group interactions proved to be constructive. Students could observe the effects of their experiments through interactive and CAD simulations. These helped them to readapt their existing mental models about the concept (Parnafes, 2010). As illustrated by the factor loadings (Table 2), moderate but positive relationships were elaborated between force and acceleration. This result was interesting since before instructions most students held an idea of force as *impetus* implying velocity already referenced in the literature (Viennot, 1979). Most students changed their idea from an *impetus* force to an *energy-like force* or an *inertial force* maintaining the motion (refining these concepts rather than replacing them). For instance, students 1, 2, and 3 mentioned energy as the cause of the motion of a projectile after it left the cannon. The knowledge structure of students 1 and 3 was not unstable since they mentioned an *inertia* and an *acceleration force* respectively during the interviews to justify the projectile motion. However, because the intervention did not approach force in relation to energy, students may hold unclear ideas between these two struggling concepts as shown in factors 1 and 2 loadings. The differences between force and energy seemed difficult to distinguish (Megalakaki & Thibaut, 2016). Another positive structure is the notion of acceleration measured by items 1, 3, and 4 (loadings > .4). This connection was made due, in part, to the support provided by the learning guidance that help students better integrate what they know with what they have learnt (Gagne et al., 2005). Conceptual resources provided by instructions were beneficial. Surprisingly, students affirmed that during the activities they learnt of the existence of Newton's three laws of motion in technology. An unexpected relationship was found between the students' notion of acceleration and the Work-Energy principle. This result could be explained in the students' sense of an *acceleration force* (through $F = ma$) that was involved in the change in kinetic energy.

The simple-to-complex sequencing showed an evolution of the student knowledge system through instructions. In the light of these primary exploratory findings, it seems that when associating different conceptual meanings about a concept (as force) in technology, students are likely to improve their understanding, thus possibly facilitating transition to the learning of concepts in science courses. In fact, technology provide opportunity to deal with a longstanding debate in student learning between concrete versus abstract instructional materials. Consequently, technology teachers should pay attention when designing explicit instructional approaches that help students learn to design, practice and develop a mixed epistemological view about a concept. The organisation and sequencing of instructional materials as well as collaboration between teachers in the construction of meanings are of great importance. Teachers often do not refer the same meanings about concepts. And since students usually perceive concepts as different among subjects, addressing epistemological meanings through a systemic approach as the 4C/ID approach do, would potentially help students develop a better structured knowledge system. A main issue resides in the construction of meanings between force and energy. For instance, there still is a confused relation between these two concepts among students that needs to be clarified (i.e. through the Work-Energy principle). When designing instruction, we suggest teachers to mention explicit relations between force and energy as they are core concepts in STEM (Science, Technology, Engineering, Mathematics).

However, this study has some limitations. First, a confirmatory factor analysis (CFA) is needed to confirm the three-factor model regarding students' ability. The chi-square index usually indicates a good fit. It was not the case in the final model since this index is sensitive to sample size (N should be > 200, or the ratio participants/items > 10). Thus, these results cannot be generalised. Second, the procedure method considered only one quasi-experimental group. Both control and experimental observations might be helpful to better capture the efficacy of both students' learning and the intervention (Myers et al., 2007). Third, many factors underlying students' knowledge structures could not be fully measured and represented.

Further inclusive interventions are needed to address a broader perspective in technology education. The model presented in Table 2 did not achieve simple structures for all the MBT items which means that students did not acquire all the knowledge learnt during the intervention. Additionally, an educational intervention based on the 4C/ID-model would need to last for longer (van Merriënboer & Kirschner, 2017) to be fully efficient. Such whole-task learning should be addressed in classrooms for the acquisition of interdisciplinary concepts in both science and technology education. Since force is also taught in physics, some students might have compartmentalised thinking linked to physics contexts of force. Despite these limitations, the study provides evidence on student learning about force in technology. Further works and analyses (i.e. student discourse) are needed to confirm some of the findings and to contribute to a better evaluation of the efficacy of the teaching approach.

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