J-STEM

Journal of Research in STEM Education

Vol 2, No 1, July 2016

j-stem.net

EDITORIAL BOARD

Contact

All queries related to manuscript submissions can be directed to Dr. Aydeniz, the Editor-in-Chief, jstemeditor@gmail.com

Mehmet Aydeniz, PhD.
Associate Professor of Science Education.
Program Coordinator, Science Education.
Department of Theory and Practice in Teacher Education
The University of Tennessee, Knoxville
A 408 Jane & David Bailey Education Complex
Knoxville, TN 37996-3442
USA
Phone: +1-865-974-0885

Publisher / Founder : i-STEM / Gultekin Cakmakci

ISSN:2149-8504

Contents

ISSN:2149-8504 (online)

Journal of Research in STEM Education

Vol 2, No 1, July 2016, PP 1

EDITORIAL

Mehmet Aydeniz[a], Lynn Hodge[a], Gokhan Kaya[b]

[a]*The University of Tenesse, Knoxville, USA*

[b]*Kastamonu University, Turkey*

We are pleased to share with you the third issue of the Journal of Research in STEM Education, J-STEM. In this issue we publish four studies, each with unique contribution to the field.

Williams and Mangan (2017) the results of a study in which they designed an intervention for young professional technologists, engineers and scientists (known as ambassadors) to visit schools and carry out a variety of interventions to educate and encourage students to choose STEM careers in New Zeeland.

The second article written by Yasar (2017), Epistemological, Psychological, Neurosciences, and Cognitive Essence of Computational Thinking provides a motivating and provocative argument about the conceptualization of Computational Thinking (CT). He draws from epistemology, psychology and neuroscience literature to advance his argument and call for conceptualizing of CT. He raises some important questions about the direction the field is taking.

Gale and colleagues (2017) report on the outcomes of a project in which they made middle school students use LEGO robotics to complete a series of investigations and engineering design challenges to deepen their understanding of key force and motion concepts (net force, acceleration, friction, balanced forces, and inertia) at Georgia Tech.

Finally, Ting (2017) proposes a model for implementing STEM in the classroom based on an engineering design perspective and for the purpose of students to acquire real-world problem-solving skills by engaging them in an engineering design process, in which students use the technology tools of graphic-based programming.

Collectively these studies, present unique perspectives, models and raise important questions about ways in which we can advance the field. These ideas contribute to ongoing efforts to further make sense of STEM as an integrated concept and as distinct content areas that share common dispositions and practices.

ISSN:2149-8504 (online)

Journal of Research in STEM Education

Vol 2, No 1, July 2016, PP 2-18

RESEARCH REPORT

The Effectiveness of Using Young Professionals to Influence STEM Career Choices of Secondary School Students

P John Williams[a1], Jenny Mangan [b]

[a]*Curtin University, Australia;* [b]*University of Waikato, New Zealand*

Abstract: *There is a concern in many countries that secondary school student interest in careers in the STEM areas is declining. In response, a program has been developed in New Zealand for young professional technologists, engineers and scientists (known as ambassadors) to visit schools and carry out a variety of interventions to educate and encourage students to choose STEM careers. The interventions include careers talks and classroom activities, organized by regional facilitators who are employed by the Institution of Professional Engineers New Zealand (IPENZ) to co-ordinate the programme across New Zealand.*

The goal of this research was to ascertain whether ambassador interventions are influential on students' attitudes to careers and curriculum choices in school. The objectives were 1) To investigate the impact of the interventions on students' views and perceptions of STEM careers; and 2) To discover any specific factors that must also exist in a given context for an intervention to be effective.

The main finding was that the ambassador interventions were influential on student career decision processes, though not all students were influenced. The facilitators work effectively in recruiting, training, organizing and supporting the ambassadors, and the ambassadors belief in the value of what they are doing helps ensure effective interventions.

The research outcomes are presented as a range of recommendations.

Keywords: Formative assessment, dialogic classroom, feedback, responsive teaching

There is general concern in many countries that declining numbers of young people are choosing a tertiary education in science, technology, engineering and maths, and this will result in downward trends in economic indicators. Aligned with advances in technology that are increasing ubiquitous and disruptive, the need for a highly trained STEM workforce and a STEM literate population are perceived as essential (Commonwealth of Australia, 2015; International Technology Education Association, 2009).

In many countries, organizations have been established to coordinate the significant range of activities related to the promotion of STEM (Australia's Chief Scientist; US Government Committee on Science, Technology Engineering and Math Education; UK Science, Technology, Engineering and Mathematics Network (STEMNET)) in order to develop synergies between the activities and so attempt to maximize impact.

In New Zealand, and in other countries, this concern has resulted in a range of STEM initiatives to: address low numbers of students entering engineering (Johnson and Jones, 2006; Joyce, 2014), clarify and enhance the STEM pipeline from secondary to tertiary education (Strawn & Livelybrooks, 2012), provide

[1] Faculty of Humanities, School of Education, Bentley Campus, 501.Level 4, Curtin University, Australia. E-mail: Pjohn.Williams@curtin.edu.au

Williams, P. J., & Mangan, J. (2016). The effectiveness of using young professionals to influence STEM career choices of secondary school students. *Journal of Research in STEM Education*, *2*(1), 2-18

teacher professional development focussed on STEM (National Education Association), develop STEM curriculum materials (see for example stem.org.uk), as well as other initiatives designed to facilitate innovation and creativity in education, business and industry and to streamline the commercialization of research.

The purpose of this study is to evaluate the effectiveness of a program in which early career professionals in the STEM areas (ambassadors) visit schools to share with students the nature of their work and to engage the students in activities related to their career, in an attempt to encourage positive attitudes in school students toward careers in the STEM areas.

Literature Review

In New Zealand, Jones (2012) has pointed out that it is important for governments to find ways to encourage able students into STEM subject areas, as well as create an environment where scientists and engineers are valued within society. Declining popularity of engineering degrees among undergraduates in Australia and New Zealand is a trend duplicated in the United States and in most Western European countries. This shortage concern is increasingly widespread, particularly in industrialised countries (Sjøberg, 2010). In Europe, Bowen Lloyd & Thomas (2003) found most Year 12 students had little perception of engineering as a career option and had received little or no advice about the engineering profession. Furthermore, as a result of poor careers advice, students who had expressed an interest in engineering were often not studying relevant subjects to make them eligible for entry into an engineering degree.

It was reported in New Zealand media (New Zealand Herald, 2013) that "the shortage of engineers is the consequence of a long-term under-investment in engineering graduates. The percentage of total graduates who choose engineering is lower in New Zealand - 6 per cent - than any other country in the OECD, which averages 13 per cent." Although the importance of STEM for the foundation of society as well as for everyday life has continued to grow, the gap between the understanding of STEM from creators of technology (engineers) and technology consumers and users has widened. This gap is also reflected in young people's understanding of what scientists and engineers actually do. In addition, there is a strong international trend to negative attitudes towards STEM education in secondary students from Western developed countries (Sjoberg & Schreiner, 2010).

The five year UK based Aspires project (Archer, DeWitt, Osborne, Dillon, Willis & Wong, 2013) revealed understandings about the development of young people's (10-14 year olds) aspirations to science related careers. They found that of this group only 15% aspire to become a scientist, in a context where there is no evidence of a poverty of aspirations, and widely held positive views about studying and learning science. Family and friends were found to play a key role influencing students' aspirations, and most are not aware of where science can lead after school.

Careers in STEM tend to become less appealing as students progress through their schooling (Baram-Tsabari et al., 2009) and many programs have been developed in an attempt to encourage positive attitudes toward STEM careers (Baker, 2013; Fadigan & Hammrich, 2004). In an Inquiry-based Science and Technology Enrichment Program analysed by Kim (2015), 83% of the middle school-aged girls involved said that their interest in science changed from negative to positive, indicating that even short (1 week) targeted interventions can have an effect. A longer term project in which high school students finish their last 2 years of high school in conjunction with their first 2 years in college indicated that participants had STEM dispositions more similar to STEM education professionals (Christensen, Knezek & Tyler-Wood, 2014).

When mentors employed in the STEM areas interact with students, there are indications that students are positively influenced toward STEM careers. At the King David School in Australia a mentor program has positively influenced student attitudes toward STEM (Cerovac, 2013). A one day event for middle school students at the Princeton Centre for Complex Materials resulted in more positive attitudes toward science and scientists (Greco and Steinberg, 2011). So there are indications that targeted interventions have an effect on student attitudes.

The Futureintech program in New Zealand has a clear objective to bridge this gap and help students develop positive attitudes toward STEM. A significant part of the Futureintech program is the interventions in schools carried out by 'ambassadors' who are practising scientists, technologists and engineers. Previous research into the effectiveness of the ambassadors' interventions (The University of Auckland, 2007; Robertson & Bolstad, 2010) provided a range of conclusions. These included that teacher demand for interventions is approaching the programme's capacity in the large urban areas of Auckland and Christchurch; STEM careers interventions are likely to have greatest impact on students' education/career decisions when delivered before age 14; students are deciding whether or not to continue with STEM subjects before Year 10; student attitudes to ongoing science learning are likely to consolidate in Years 7-8; students' decisions about whether or not to continue with STEM subjects are significantly influenced by their family, and Year 12-13 students who are studying STEM subjects need specific information to make further study choices.

The research described in this paper was conducted in order to interrogate the views of the students, to a greater degree than this earlier research, on the impacts of the interventions on their interest in STEM careers, and to discover any specific factors that must exist in a given context for a Futureintech intervention to be effective.

Research Paradigm

This research uses an interpretivist paradigm (Denzin & Lincoln, 2000) which is supportive of constructivist philosophical approaches. Such approaches share the notion that reality is a social construction, created by members of a community, and that lived experiences need to be understood from the perspective of the participant observer.

This evaluation research, carried out in an education context, is infused with a multitude of human values and beliefs, and appropriately so within a constructivist framework. The researchers strove for the representation of all stakeholder views in a fair and balanced way. As constructivist researchers, there is a recognition that "truth is greatly constrained by the time, context and particular experiences of the stake holding community that generated it" (Guba & Lincoln, 2004, p. 231).

Consequently, because of the situated nature of the study, no attempt is made at generalization by the researchers. This does not mean that the findings and recommendations are not useful to other practitioners in other contexts, but it is up to the reader of this research to determine its applicability to their context.

Methodology

There are many approaches to evaluation research (Mathison, 2004; Fleet (2001) but two broad categories are those commonly recognized as formative and summative. A formative evaluation is a method for judging the worth of a programme while the programme activities are in progress. According to Boulmetis and Dutwin, (2005), formative evaluation is an on-going process that allows for feedback to be implemented during a programme cycle. Summative evaluation is a method of judging the worth of a programme at the end of the programme activities. This research utilizes a mix of summative and formative evaluation research strategies, contextualized in this research in Figure 1.

Research Questions

The main research question was:

> Are ambassador interventions more or less influential on students' attitudes and choices related to STEM careers?

And the subsidiary question was:

> Are there any specific factors that must also exist in a given school/class for an intervention to be effective?

ISSN:2149-8504 (online)

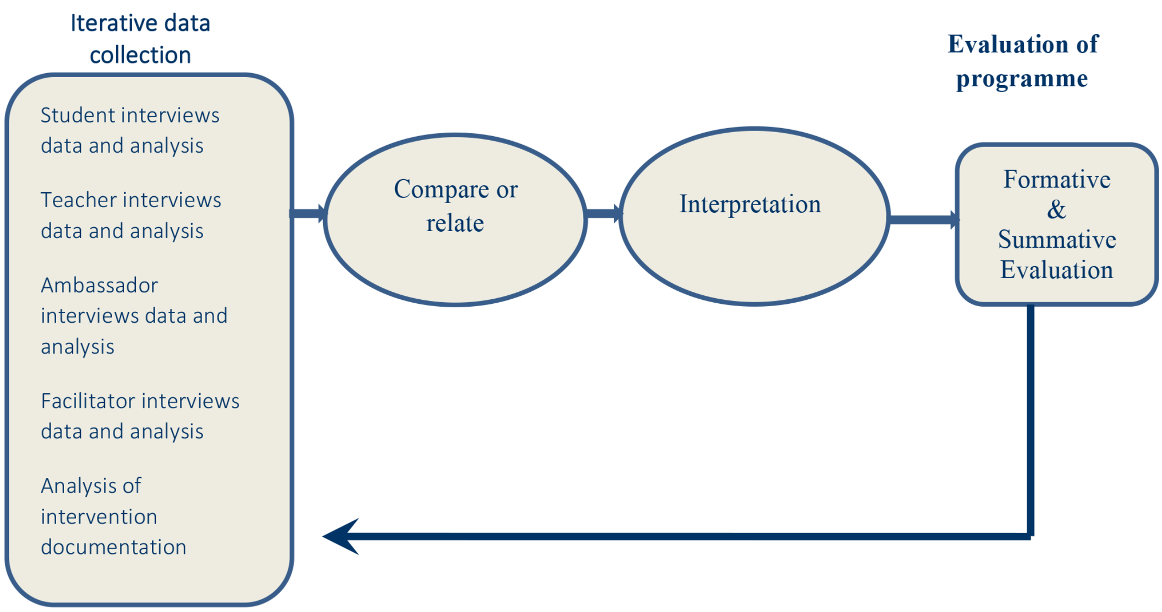


Figure 1. Methodology adapted from mixed-methods convergent parallel design

Participants

There were five groups of participants in the research:

Facilitators : IPENZ staff, who organised and facilitated the ambassador intervention programme.

Ambassadors : experts from industry, who give their time to provide presentations and workshop activities.

Teachers : classroom teachers, who provided the facilities and timetable release for students to attend the interventions.

Students : school children, who participated in the interventions offered.

Researchers : the evaluation experts, who attended the scheduled interventions and evaluated the programme.

Table 1 summarises the characteristics of the schools and the number and year of the students that were involved in the school visits observed by the researchers.

Table 1.

Characteristics of schools and participants.

Location	Type*	Decile#	School Population	Year	Students In activity	Activity
urban	sec	1	1313	9	40	Career talk & technology challenge
urban	sec	1	1313	10	20	Career talk & technology challenge
urban	sec	1	1200	12	30	Career talk & technology challenge
urban	inter	6	628	7	30	Career talk & process flowcharting
rural	Sec	2	424	12	23	Talk on algebra use in engineering
urban	prim	1	627	7	39	Experiments related to acids & bases
urban	prim	1	630	8	70	Experiments related to acids & bases
urban	sec	1	1581	13	17	Talk on Antarctica.
urban	sec	8	2167	13	18	Career talk
rural	sec	2	760	8	20	Programmable Xmas Tree activity
urban	sec	6	1219	13	17	Career talk by 2 engineers
urban	sec	10	2553	10	30	Career talk by 2 engineers
rural	inter	9	699	13	24	Career talk

*Schools are classified as primary (year 1-8), intermediate (year 7-8) and secondary (year 9-13).

All schools are rated in a socio-economic band where 1 is the lowest and 10 is the highest.

Data collection

An interpretative approach to the perceived reality, which is co constructed within a community, influenced the research questions; the choice of research methodology; and the methods of data collection, generation and analysis. The evaluation methodology utilised in this report was designed to inform both formatively and summatively through data collection, analysis and reflection.

The thirteen interventions which are the subject of this study were attended by over 350 students across intermediate, secondary and primary schools located in North, Central and Southern regions of New Zealand. Ethics permission was sought and gained from all participants, including the parents/guardians of underage students. Interviews were conducted with focus groups (4-6) of students at all thirteen interventions. In-depth interviews were conducted with five facilitators, twenty one ambassadors and thirteen teachers. All interviews were audio recorded and transcribed into MS Word documents.

The project comprised multiple forms of data collection, including:

- Pre-intervention, semi-structured focus group interviews with students;
- Post-intervention, semi-structured focus group interviews with students;
- Post-intervention, interviews with ambassadors;
- Pre-intervention, interviews with teachers;
- Post-intervention, interviews with teachers;
- Pre-intervention, semi-structured interview with facilitators;
- Post-intervention, semi structured interview with facilitators;
- Intervention observational field notes;
- School brochure/prospectus;

ISSN:2149-8504 (online)

- Principal semi-structured interview;
- Copy of ambassador PowerPoint.

Researcher observation of the intervention programme was an important source of qualitative data for evaluation. The main purpose of the observation was to obtain a thorough description of the intervention programme including the activities, and the involvement of the participants. It involved careful identification and description of relevant human interactions and processes.

Semi-structured interviews involved the preparation of an interview guide that listed a pre-determined set of questions or issues that were to be explored during the interviews. This guide served as a checklist during the interview and ensured that basically the same information was obtained from a number of people. Flexibility was possible as the order and the actual wording of the questions was not determined in advance, and within the list of topic or subject areas the interviewer was free to pursue certain questions in greater depth. The advantage of the interview guide approach is that it makes interviewing of a number of different persons more systematic and comprehensive by delimiting the issues to be taken up in the interview. Logical gaps in the data collected can be anticipated and closed, while the interviews remain fairly conversational and situational.

Focus group interviews were conducted with small groups (4-6) of students, who were asked to reflect on the questions asked by the interviewers, provide their own comments, listen to what the rest of the group had to say and react to their observations. They were interviewed before and after the ambassador's visit where the timetable permitted such access. It was attempted to ensure that at least some of the same students were included in both the before and after groups. The focus groups were either purposively selected on the basis of the teacher's recommendation, or conveniently selected in terms of who was available within the school timetable restrictions. The main purpose was to elicit ideas, insights and experiences in relation to the interventions they experienced. The researchers acted as facilitators by introducing the subject, guiding the discussion, cross-checking each other's comments and encouraging all members to express their opinions.

The researchers supplemented the observation notes and interviews with documentary material, namely the school brochure which provided a record of the demographics of the school, and a copy of the ambassador PowerPoint which served as a record of the nature of the intervention.

Findings

In order to provide a clear understanding of the nature of the intervention activity, it will be presented in a chronology of preparation for the intervention and then the intervention itself, and then these elements will be integrated in the discussion and conclusion in order to answer the research questions.

Preparing for the Intervention

There is a general approach taken to establishing a school visit by an ambassador. The facilitator gets agreement from the ambassador a month or so before the visit. Then two weeks and again two days prior, information related to the details of the school location and access are sent and copied to the teacher.

Some facilitators work very closely with specific schools to the extent that the school teacher selects the ambassadors they want.

> *Each year, I work with the head of science and we kind of try and get to as many of the senior science classes as we can, so I probably have six to eight ambassadors that do multiple talks to different classes. I plan it out with the HOD and he chooses the ambassadors that he wants, I give him a list of some of the potential people and then he picks from those and then I set it up.*

The general attitude of facilitators is that they are happy to support the curriculum, but the main purpose is to promote career awareness. One ambassador had received a list of topics from the teacher that the students had studied so far this year, and he used that as a reference in his presentation:

ISSN:2149-8504 (online)

Cause yeah, I thought okay, they've learnt about this, maybe we should show them how it works in the real world.

The students then seemed to more easily relate to the presentation because of the link it provided with their previous studies.

However, few of the teachers interviewed had done any significant preparation for the intervention visit other than organizing the time and location, even though they recognized that the integration of the content of the ambassador visit into their lesson planning would have advantages. Some indicated that in the following year they would plan the time of the ambassador visit to align with the student subject selection process, in an attempt to increase their enrolments in upper school science subjects.

Student anticipation of what the session was going to focus on depended on the extent to which the teacher had prepared the class for the visit, so consequently varied from 'no idea' to a quite specific anticipation such as 'We're building an electronic Christmas tree'. The majority of students who had some idea of what the visit was going to be about had pre-conceptions related to content (engineering, physics, food, bio-robotics) rather than careers.

About half of the students interviewed before the visit had not done any preparation for the ambassador visit. The majority of those who had done some preparatory work had been asked to think of some questions that they might like to ask the ambassador. Others seemed to have done some preparatory work, either with a focus on careers, or on content:

We did something yesterday - we just looked at some jobs in biology, like if you're doing biology.

We also read, like a booklet, and it tells you about what jobs can you do.

There was no obvious indication that this type of superficial preparation had any effect on student engagement during the intervention, nor on a more positive interest in STEM careers. However, in those classes in which the teacher had more thoroughly integrated the intervention (for example including a follow up questionnaire, and integrating it with course content) it was obvious to the observers that the students were more engaged during the intervention, and the teachers reported that the students were more impacted by the STEM career message.

As would be expected in the case where most of the ambassador visits were to science classes, the majority of the students favoured science related subjects, as shown in Table 2.

Table 2.

Students' favourite subjects

Subject	**%**
Sciences	26
English	12
Maths	19
Art / drama	12
Technology	12
PE	11
Other (sport, economics, history)	8

Despite the feeling of the teachers and facilitators that an ambassador visit, which was aligned with the curriculum currently being studied, would have more impact on students than a single unrelated visit, there was no consistent effort to ensure that there were links between the curriculum and the topic of the ambassador visit.

ISSN:2149-8504 (online)

The Intervention

There were some teachers who seemed to be using the experience as a 'filler' or an excuse for a change of routine. These teachers tended not to get involved in the presentation and either sat at the back of the room or used the time to catch up on other things.

> *… 'cause we're towards the end of the year, we've kind of finished all our external prep and we've just got an internal [activity] left to do with my year thirteens for sort of a bit of a break at the end of the week; on a Friday it's sometimes difficult to get them doing anything, so I think they're happy to sit there and have a listen, yeah.*

The researchers observed that the students seemed to be more focussed and engaged in those interventions with which the teacher was involved.

Cool, awesome, interesting, good, and enjoyable were the most common adjectives used by students to describe the ambassador visit. There were no negative responses from the students related to the visits, which could be because the students with negative feelings remained quiet, but it seemed to the researchers that the students were quite disclosing in their feedback. One student did comment, with some surprise, that, unlike some other presentations, this one was not boring, and was actually good compared with the others.

Some of the students went a little deeper in the post-visit discussion, and indicated that it was engagement with the activities that was the most positive feature for them.

> *I liked the fact that she got us really involved; like, sometimes when you find stuff like that you don't get very involved but like all the class and stuff that we have had have been like really involving us.*

Other students responded more to the career related goals of the visit, and thought it was those aspects which made the presentation positive for them.

> *It kind of gave some insight into how many different - like, how different skills go into his job kind of like the different types of stuff that go into what he does like in management and engineering and that kind of stuff.*

Some students found the specific job that was discussed interesting, or information about the specific job was aligned with their interests.

> *It was a very interesting job, the way how they managed to get something as simple as sand and turning it into something that could change the world.*

A number of students mentioned that a memorable aspect of the presentation was how the job information was related to the broader context, and often it was an environmental/ sustainability context that appealed to them.

> *I think it was really cool and I liked seeing what they did in their jobs and how it affects the environment and how they did it.*

> *It's cool to see like, what elements are in like, around the world in the environment and how you could use those to benefit our lives.*

There were two broad categories that summarized what the students felt were the best parts of the presentations: one related to the physical or practical aspects (*the machine, the dry ice, the structure, the bubble stuff, etc.*); the second, and less significant category was about the job – *learning about it, how many jobs there are, all the different things she got to do*. A not uncommon response was: *I just liked all of it*.

When asked what could have been better about the program, a range of responses were recorded, but this was mostly in a positive and constructive context, and about 30 percent of student interviewees indicated that there was nothing that could have been done better. While many of the ambassador visits were accompanied by some kind of activity, some were just a discussion based around a PowerPoint presentation,

ISSN:2149-8504 (online)

and some students felt that there should be some activity associated with this kind of visit, and reported that this would make it more engaging.

A quite common theme from students in different schools after the presentations was that engineering seemed like fun: engineering sounds fun. This perception, however, did not always translate into career affinity: *It's really fun but I don't think I'll be able to do, like, be able to do it myself.*

Of those students who indicated that the presentation had influenced them to consider a STEM career, their reasons were as various as the number of students.

> *Oh yeah, 'cause I wanted to do law and that but that doesn't really involve maths but I like maths, and engineers involve that, engineering and that involves maths so I might look towards that.*

> *I'm still not exactly sure what I want to do but it does give me some idea where I want to kind of be.*

A number of ambassadors incorporated some form of related activity within their presentation, and they had various goals in mind with that approach. One just wanted the students to have a positive STEM related experience that they found interesting, and could take away a feeling of some success that they had achieved a technological outcome. Others recognized that students get more engaged with their presentation if there is an active element to it, thinking that this engagement would translate into a higher degree of impact about STEM careers.

Of the students interviewed, 65 percent stated that they were interested in a career in a STEM area. Their intentions varied from the general (something to do with science) to a quite specific career area (geologist, chemical processing engineer). Twenty percent of the students had career aspirations in areas other than STEM, and these spanned a broad spectrum from rugby player, actor, teacher, and 'something in commerce'. There were a number of students who had ideas which were clearly unresolved:

> *I want to be an actor or someone who studies cancer and stuff like that to find cures for cancer.*

> *And I'm probably looking at commerce now, but that's changed throughout the year - I was looking at civil engineering at the start of the year.*

> *It's sort of a process of elimination for me - I didn't really want to do med, I'm not particularly interested in law so ... yeah. It's engineering.*

> *Because I was planning on trying to be an author or an English teacher but the thing was, I like science, okay, so I'm like maybe yes, maybe no, I'm not sure yet.*

For many of these students it seemed that they needed assistance and more information in order to help them clarify their career aspirations. Of the students interviewed, 15 percent were not sure what career they wanted to pursue.

For almost all students, their reference point for their career aspirations was what they enjoyed, and that became the basis of their (sometimes rather vague) career direction. For example:

> *I really enjoy maths and science.*

> *I find maths a little bit boring.*

> *I've kind of always been interested in programming.*

> *I've just always really liked science.*

> *I just like it and I want to do psychology, [it's] just interesting.*

Apart from 18 percent of students who didn't know where to go for more career information, students indicated there was a wide range of sources of information (Figure 3) for career advice.

Table 3.

Sources of information for career advice

Information Source	%
Don't know	18
Careers Expos/days	15
School Careers Centre	9
Teachers	10
Professionals	10
Internet	17
Universities	5
Other (parents, brochure etc.)	16

Feelings about the optimum age of the students who benefit most from an intervention varied, but age was also recognized as critical:

Before their subject choice, they need to meet some people, so that's why I've targeted either year nine, ten, sometimes eleven - before you split the sciences 'cause that's when you either shut down or remain open your science potential.

Other facilitators felt that a range of age groups benefit for different reasons:

I reckon the year seven, eights is crucial so that's my next push, so I've got into most of the science classes at the junior level.

This same facilitator was also working with year 12 physics classes at a girls' high school, and reported that the girls were very responsive:

The girls were like, oh! We never knew, you know, everyone said I should do Health Science; well, actually I didn't know about the engineering.

Despite the difficulty of evaluating the impact of ambassadors' visits on career choice, facilitators were adamant that their main goal is to influence career choice. The facilitators considered that there are many variables that come together to make an intervention impactful on students' attitudes to STEM careers, such as:

- Teacher interest – if an intervention is imposed on teachers it does not provide a context for maximum benefit.
- Integration with school curriculum – when school structures support the ambassador visit, the effects seem to be enhanced. At one school the teacher had integrated the ambassador's presentation into the curriculum and had developed a questionnaire for students to complete in conjunction with the presentation. The ambassador recognized that this enhanced his presentation. At another school:

  The Principal set up this last year where it's project time for year nines on Thursday morning and project time for year tens on a Friday and the engineers will go in and look after them - they'll mentor their kids with a specific teacher, that's the same teacher each time. The Principal argues that these kids are very excited about working in computer science, software engineering or electronics as a result.
- Position within a broader context – if a school has a careers day or has a number of activities focussed on careers during a week; facilitators felt that this contextualization has more of an impact on students than a one-off presentation.
- Exposure to a number of ambassadors over time – some facilitators thought that a number of ambassadors' visits over a period of time from a range of professional contexts provided students with a broader picture of STEM careers and so more adequately provided a range of contexts with which they

ISSN:2149-8504 (online)

could identify.

- A series of activities – one facilitator attempted to organize the ambassador's visit as just one part of a series of structured activities:

  One period was spent browsing our websites and another period was listening to a couple of people from the industry, and another one is perhaps reading the brochures and answering questions and doing little group activities.

- A long term project – in one city a company provided funding for electronics kits for students, which they work on over a period of time. The facilitator organizes for ambassadors to visit the students about once per fortnight, and sees this project as getting maximum benefit because of the emotional involvement by the students in being able to keep their programmable kits.

Commonly cited evidence for effectiveness was related to the developing numbers of '360 ambassadors'. These are current ambassadors who are working and engaged in the Futureintech programme, and can recall being directly influenced in their choice of career by an ambassador visit when they were in school. One facilitator recalled that there were about 35 of these 360 ambassadors.

I've got an ambassador who's just started working. She finished uni last year, she was at ... where I ran some talks so the parents would go into a classroom and listen to some talks, and she was there with her mum listening to a foodie and said 'That's what I want to do' and bam! She did it.

All of the ambassadors felt that they would have had an influence on at least some of the students, but not all, as it was often clear that in all groups there were at least some students who had a clear idea of their future career path. This was confirmed by the students, 25 percent of whom said the visit had no influence, 50 percent said it was influential, and for 15 percent, it confirmed what they were already thinking. A significant proportion of both the NO and YES categories already had firm career ideas in mind prior to the program.

Of the students who provided feedback through the interviews, 60 percent indicated in the pre-intervention interview that they were considering a STEM related career, and 73 percent indicated this in the post-intervention interview. These were not always the same students in the pre and post interviews, so it is not a matched sample. However, even when interpreted cautiously, this is one indicator of the effectiveness of the intervention in this regard.

About 20 percent of students did not know where they would go to get more career information. The most common response from those who did have some idea was a teacher, generally, or a specific teacher such as physics. Other responses encompassed the predictable range of library, the careers room or teacher, or computers. In one school, there was a general consensus that the careers advisor is very condescending; she's not that useful to be honest.

The ambassador visit met or exceeded the expectations of most of the teachers, the criteria being the level of engagement of the students. Engagement was most pronounced in those interventions that included hands-on activities.

Discussion

The researchers observed the variety and flexibility of the interventions conducted throughout New Zealand during the six month period of the research, both in terms of activity and also in age appropriateness. The form of the interventions varied from formal career talks and technology challenges, through to full day and extended project-based learning activities. Each intervention was professionally facilitated, all participants endeavoured to create an influential learning experience for the students involved. The interventions occurred in a variety of schools including single and coeducational, intermediate and secondary as well as a range of different socioeconomic ratings. The content areas of intervention included: civil engineering, mechanical and structural engineering, chemical engineering, water treatment engineering, electrical engineering, plant and

ISSN:2149-8504 (online)

food research scientists, and transportation engineering.

The facilitators were enthusiastic, conscientious, knowledgeable individuals who are an essential major component in any successes achieved by the intervention programme. They attract new ambassadors; they liaise with the industry partners to ensure they have a good understanding of the important role they play in the success of the endeavours. They provide ambassadors and teachers with support pre- and post-intervention, which helps to avoid any potential problems or issues that could easily arise.

The majority of teachers observed during the evaluation period were willing and open to receiving the interventions. They endeavoured to meet the practical and logistical requirements that each different intervention required. The senior management of the schools played a minor role in the interventions, but the feedback from teachers indicated a positive supportive disposition towards the program.

The industry experts observed during the evaluation period were young enthusiastic ambassadors who have been generous with their time and support for the Futureintech programme. Each has commented positively about the intended outcomes and the personal benefits they received from giving of their time and energy.

The students have, in the main, been willing participants in the interventions: many have shown insight and appreciation for what has been done. The intervention programme was shown to be an effective model from the perspectives of all the participants involved.

Recommendations

While it is clear that the program does influence student career choices in STEM areas, not all the interventions were as successful as they could have been and some themes have emerged to inform the recommendations.

1. Students recalled prior ambassador visits positively, and were almost exclusively positive about the observed visits. Engagement was a key factor in their positivity, either through activities which were part of the presentation, or just through involvement in the presentation itself. In students' suggestions about what could have been done better, engagement emerged again as a key criteria. As a result it was recommended that where possible the interventions contain both career talks and related practical activities with which students can engage, providing that the link between the two is made explicit (Millar, 2002).
2. Presentations that contextualized the ambassador's career into a broader career context rather than focussing narrowly on their specific job, appealed to students and would also, potentially, appeal to a broader range of students. As a result it was recommended that the ambassadors discuss the range and opportunities of STEM related activities in their enterprise as well as the specifics of their individual job.
3. Not all students recognized that the purpose of the visit was related to helping them make informed career choices, especially those visits that were mainly activity based where the ambassador spoke only for a short time about themselves and their career. This is despite both facilitators and ambassadors being quite adamant that career awareness was the priority for all the visits and activities, and some facilitators, but not all, ensured this in the introduction of the ambassador to the class. Despite the ambassadors all recognizing that STEM career awareness was the goal of their visit, this did not always come across to students. As a result it was recommended that greater attention be given to pre and post intervention career related activities.
4. About half the students had done some preparatory work for the visit, and this was most commonly to think of some questions. This was reinforced by the facilitators who only organized communication

ISSN:2149-8504 (online)

between the ambassador and the teacher if they were preparing for a curriculum related visit. The ambassadors did not feel that prior communication was necessary, although they recognized that when curriculum links were made, their message was more effective. As a result, and considering that advance organizers facilitate learning and retention (Luiten, Ames & Ackerson, 1980), it was recommended to facilitate meaningful communication between the ambassador and the teacher prior to the school visit to devise methods to prepare the students.

5. Of the students, 65 percent were interested in a STEM career, 20 percent were interested in careers other than STEM, and 15 percent were not sure what career they wanted. The visits seemed to generally confirm those who were already interested in a STEM career, and rarely changed the ideas of those who were thinking of a career outside the STEM areas. The 15 percent undecided are the real target for the interventions. As a result it was recommended that where possible in schools, ambassador visits be organised for those students who declare they are undecided about their career aspirations.
6. The pre-visit interview revealed that almost one fifth of students didn't know where to go for more career information, and this ratio didn't change after the visit. Some facilitators handed out information after the visit, but this did not happen in all cases and seemed a little rushed when it did occur, with students wanting to get out to lunch or the next class. As a result it was recommended that a clear strategy be developed and implemented to ensure additional STEM career information including the website are always identified for the students at interventions, and further connections are developed with career advisors in schools.
7. Facilitators and teachers felt that both the younger (years 7-8) and older (years 10-11) groups were both important targets for ambassador visits. This reinforced previous research by Robertson & Bolstad (2010). As a result it was recommended that a greater focus be placed on these age groups – Years 7-8 because the children were more open to STEM career opportunities, and Years 10-11 because this is often where the students are making subject choices.
8. All the ambassadors observed had followed university pathways into their STEM career. With the increasing diversity of pathways available to students into the STEM professions (Fealing, Lai & Myers, 2015), it would seem that ambassadors with alternative pathways would provide some students with a broader range of relevant information. The use of these ambassadors may necessitate a review of the target student audience to include early school leavers rather than only those progressing to the final year of school. As a result it was recommended that an additional focus be placed on alternative pathways into STEM based careers, and ambassadors be sought who have followed these pathways.

This research was mainly focussed on one aspect of an intervention programme, and was conducted on a small representative sample of the interventions that take place, therefore, it is not possible to make generalisations. However, the researchers are confident that educators in a range of contexts may be able to apply some of the findings to their situation.

Overall, all participants involved in the ambassador intervention programme were very positive about the experience. Teachers, facilitators and the early career ambassadors, working together, enabled students to be positively influenced.

ISSN:2149-8504 (online)

Conclusions

The research questions were:

Are ambassador interventions more or less influential on students' attitudes and choices related to STEM careers?

The indications from the data are that ambassador interventions are generally influential on student STEM-related career choices, but not all students. Some students have fixed preconceptions about their career aspirations which are not amenable to change.

Are there any specific factors that must also exist in a given school/class for an intervention to be effective?

There seem to be a range of factors, outlined in the recommendations, which combine to make interventions effective. The most significant factor is individual student receptivity regarding career choice. If they have made up their minds about their career, then the interventions may have little impact. However, if seen as part of an overall career choice strategy including printed and online materials, it offers some clear benefits. For those who are considering a STEM career it helps to reinforce and validate their decision making. For those who have never considered a STEM career it is a good introduction and may encourage students to investigate further.

Acknowledgements

The authors would like to thank the professional association of engineers in New Zealand (IPENZ) for funding this research, Gary O'Sullivan for his research guidance, and all the ambassadors, facilitators, teachers and students for their willing participation.

References

Angen, M. J. (2000). Evaluating interpretive inquiry: Reviewing the validity debate and opening the dialogue. Qualitative Health Research, 10(3), 378-395.

Archer, L., DeWitt, J., Osborne, J., Dillon, J., Willis, B. & Wong, B. (2013). Aspires: young peoples science and career aspirations, age 10-14. London: Kings College.

Archer, L & DeWitt, J. (2017) Understanding Young people's science aspirations. London: Routledge.

Baker, D. (2013). What works: using curriculum and pedagogy to increase girls' interest and participation in science. Theory into Practice 52(1):14–20.

Baram-Tsabari A., Sethi R.J., Bry L., Yarden A. (2009). Asking scientists: a decade of questions analyzed by age, gender and country. Science Education, 93(1):131–160

Boulmetis, J., & Dutwin, P. (2005). The ABCs of evaluation (2nd ed.). San Francisco, CA: Jossey-Bass.

Bowen, E., Lloyd, S., & Thomas, S. (2003). Broadening access among lower socio-economic groups in higher education: A European funded approach. Journal of Widening Participation and Lifelong Learning, 5(2), 46 - 49.

Cerovac, M. (2013). Shaping Australian secondary students attitudes toward STEM. Proceedings of the 64th International Astronautical Congress, Volume 12, 2013, Pages 9532-9541.

Christensen, R., Knezek, G. & Tyler-Wood, T. (2014). Student perceptions of Science, Technology, Engineering and Mathematics (STEM) content and careers. Computers in Human Behavior, 34, 173-186.

Cohen, C., Patterson, D., Kovarik, D. & Chowning, J. (2013). Fostering STEM career awareness: emerging opportunities for teachers. Washington State Kappan 7(1), 12-18.

ISSN:2149-8504 (online)

Commonwealth of Australia (2015). National Innovation and Science Agenda. Canberra: Author.

Denzin, N. K., & Lincoln, Y. S. (Eds.). (2000). The handbook of qualitative research (2nd ed.). Thousand Oaks, CA: Sage.

Denzin, N. K., &, Lincoln, Y. S. (Eds.). (2008). Collecting and interpreting qualitative materials (3rd ed.). London, England: Sage.

Eisner, E. W. (1991). The enlightened eye: Qualitative inquiry and the enhancement of educational practice. New York, NY: Macmillan.

Fadigan, K.A. & Hammrich, P.L. (2004). A longitudinal study of the educational and career trajectories of female participants of an urban informal science education program. Journal of Research in Science Teaching, 41:835–860

Fealing, K., Lai, Y. & Myers, S. (2015). Pathways vs. pipelines to broadening participation in the STEM workforce. Journal of Women and Minorities in Science and Engineering, 21(4), 271-293.

Geertz, C. (1973). The interpretation of cultures: Selected essays. New York, NY: Basic.

Greco, S. & Steinberg, D. (2011). Evaluating the impact of interaction between middle school students and materials science and engineering researchers. Materials Research Society Symposium Proceedings, Vol 1364, 39-45.

Guba, E. G., & Lincoln, Y. S. (1989). Fourth generation evaluation. Thousand Oaks, CA: Sage.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In N. K. Denzin, & Y. S. Lincoln (Eds.), Handbook of qualitative research (pp. 105-117). London, England: Sage.

Guba, E. G., & Lincoln, Y. S. (2004). The roots of fourth generation evaluation. In M. C. Alkin (Ed.) Evaluation roots: Tracing theorists' views and influences (pp. 225- 241). London, England: Sage.

International Technology Education Association. (2009). The overlooked STEM imperatives: Technology and engineering K-12 education. Retrieved from: http://www.asd.k12.pa.us/cms/lib6/PA01000584/Centricity/Domain/994/STEM_Guide.pdf

Johnson, W.C., & Jones, R.C. (2006). Declining interest in engineering studies at time of increased business need. In L.E. Weber and J.J. Duderstadt, (Eds). Universities and business: Partnering for the knowledge society. London, England

Jones, A. (2012). Risks in narrow focus. Waikato Times, 24 May 2012. http://www.stuff.co.nz/waikato-times/opinion/columnists/6976563/Risks-in-narrow-focus

Joyce, S. (2014). Campaign to boost engineering study at polytechs. Wellington, NZ: New Zealand Government. https://www.beehive.govt.nz/release/campaign-boost-engineering-study-polytechs

Kember, D. (2000). Action learning and action research: Improving the quality of teaching and learning. London, England: Kogan Page.

Kim, H. (2015). Inquiry based science and technology enrichment program for middle school-aged female students. Journal of Science Education and Technology, 25(2), 174-186.

Kuhn, T. S (1970). The structure of scientific revolutions (2nd ed.). Chicago, IL: University of Chicago.

Lincoln, Y. S., & Guba, E. G. (2000). Paradigmatic controversies, contradictions, and emerging confluences. In N. K.Denzin & Y. S. Lincoln (Eds.),Handbook of Qualitative Research(pp. 163-188). Thousand Oaks SAGE.

Luiten, J., Ames, W. & Ackerson, G. (1980) A meta-analysis of the effects of advance organizers on learning and retention. American Educational Research Journal, 17(2), 211-218.

Mathison, S. (Ed.). (2004). Encyclopedia of evaluation. Thousand Oaks, CA: Sage Publications.

ISSN:2149-8504 (online)

Millar, R. (2002) Thinking about practical work. Ch. 6 in S. Amos and R. Boohan (Eds.) Aspects of teaching secondary science: perspectives on practice. London: Routledge Falmer

National Education Association. STEM Teacher training program. http://www.nea.org/home/stem.html

New Zealand Herald (Oct 26, 2013). Editorial. New Zealand Herald.

O'Sullivan, G. (2012). Technology and the community. In PJ. Williams (Ed.) Technology education for teachers. (pp. 167 - 196). The Netherlands: Sense.

Patton, M. Q. (1997). Utilization-focused evaluation. (3rd ed.). Thousand Oaks, CA: Sage.

Robertson, S. & Bolstad, R. (2010). The role and impact of futureintech ambassadors final report. Wellington, NZ: New Zealand Council for Educational Research

Schwandt, T. A. (1998). Constructivist, interpretivist approaches to human inquiry. In N. K. Denzin, & Y. S. Lincoln (Eds.), The landscape of qualitative research: Theories and issues (pp. 221-259). Thousand Oaks, CA: Sage.

Sjøberg, S. & Schreiner, C. (2010). The next generation of citizens: Attitudes to science among youngsters. In M. Bauer, N. Allum, & R. Shukla, (Eds). The culture of science – How does the public relate to science across the globe? New York, NY: Routledge.

Stake, R. (2004). Standards-based & responsive evaluation. Thousand Oaks, CA: Sage.

Stake, R. & Schwandt, T. (2006). On discerning quality. In I. F. Shaw, J. C. Greene, & M. Mark (Eds.). Handbook of evaluation. London, England: Sage. Retrieved July 12, 2006, from http://www.ed.uiuc.edu/circe/Publications/Discerning_Qual_w_Schwandt.doc.

Strawn, C. & Livelybrooks, D. (2012). A five-year university/community college collaboration to build stem pipeline capacity. Journal of college science teaching 41(6), 47-51

The University of Auckland. (2007). Futureintech monitoring and evaluation. Not published.

ISSN:2149-8504 (online)

APPENDIX A

PRE-SESSION STUDENT FOCUS GROUP INDICATIVE QUESTIONS

Have you been to a session like this before?
If so what did you get out of it?
What do you think the session you are doing today is about?
Have you done any preparation work to get ready for this session?

What careers are you interested in? Why?
Have you considered a career in STEM (Science, Technology, Engineering or Mathematics)? Why? Why not?
If you wanted to know about STEM careers where would you go for information?
Are there any resources in the school that could help you?

What are your favourite subjects at school?
Is your family interested in STEM? (family activities, visits, careers)
Do you think you are capable of having a career in a STEM area?

POST-SESSION STUDENT FOCUS GROUP INDICATIVE QUESTIONS

What did you think about today's session?
What were the best bits?
What bits could have been better?
Did it help you to consider a STEM career?
Did it change your mind about STEM careers?
What might influence your career choice?
Are you interested in more information about STEM careers?

Journal of Research in STEM Education

Vol 2, No 1, July 2016, PP 19-38

RESEARCH REPORT

Epistemological, Psychological, Neurosciences, and Cognitive Essence of Computational Thinking

Osman Yasar [a 1]

[a]*State University of New York, USA*

Abstract: *The construct of computational thinking (CT) was popularized a decade ago as an "attitude and skillset" for everyone. However, since it is equated with thinking by computer scientists, the teaching of these skills poses many challenges at K-12 because of their reliance on the use of electronic computers and programming concepts that are often found too abstract and difficult by young students. This article links CT – i.e., thinking generated and facilitated by a computational device – to our typical fundamental cognitive processes by using a model of mind that is aligned with research in cognitive psychology and neuroscience and supported by a decade of empirical data on teaching and learning. Our model indicates that associative and distributive aspects of information storage, retrieval, and processing by a computational mind is the very essence of thinking, particularly deductive and inductive reasoning. We all employ these cognitive processes but not everyone uses them as iteratively, consistently, frequently, and methodologically as scientists. Some scientists have even employed electronic computing tools to boost deductive and inductive uses of their computational minds to expedite the cycle of conceptual change in their work. In this article, we offer a theoretical framework that not only describes the essence of computational thinking but also links it to scientific thinking. We recommend teaching students cognitive habits of conceptual change and reasoning prior to teaching them skills of using electronic devices. Empirical data from a five-year study involving 300 teachers and thousands of students suggests that such an approach helps improve students' critical thinking skills as well as their motivation and readiness to learn electronic CT skills..*

Keywords: Deductive and inductive thinking, cognitive processes, modeling and simulation

Introduction

A decade of discourse since the launch of computational thinking (CT) initiative by the computer science community has resulted in wide acceptance of the following relevant CT skill set for K-12 education (Grover & Pea 2013):

- Abstraction and pattern generalization (including models and simulations)
- Systematic processing of information
- Symbol systems and representations
- Algorithmic notion of flow control
- Structured problem decomposition
- Iterative, recursive, and parallel thinking

[1] Empire Innovation Professor, Department of Computational Science, State University of New York (SUNY)-Brockport 350 New Campus Drive, Brockport, NY 14420, E-mail: oyasar@brockport.edu

Yasar, O. (2016). Epistemological, psychological, neurosciences, and cognitive essence of computational thinking. *Journal of Research in STEM Education*, *2*(1), 19-38

ISSN:2149-8504 (online)

- Conditional logic
- Efficiency and performance constraints
- Debugging and systematic error detection

The idea of adding computational thinking to a child's analytical ability goes back almost four decades (Papert, 1980), yet its recent popularization by Wing (2006) and federal agencies have successfully encouraged many teacher organizations and professional societies to promote its inclusion in education through learning standards (NRC Report, 2012). While the above skills may be appropriate for college freshmen, they all seem to be associated with problem solving and the use of electronic devices with an ultimate goal of preparing tomorrow's programmers. Grover and Pea (2013) attest to that conclusion by arguing that, "Programming is not only a fundamental skill of CS and a key tool for supporting the cognitive tasks involved in CT but a demonstration of computational competencies as well." They also claim that efforts that introduce computing concepts without the use of a computer may be keeping learners from the crucial computational experiences involved in CT's common practice (p. 40). While this is an admission of the fact that obstacles remain in the way of integrating CT practices into grade level curricula, we argue, in contrary to their assessment, that the mere focus on programming is the source of many obstacles in CT education.

Unresolved questions remain in computing education. If we continue to define computational thinking as thinking by a computer scientist during problem solving, then having young students learn problem solving the way that computer scientists do will continue to pose challenges. These challenges are many, including a) prerequisite CS content knowledge needed to engage in the same thinking processes as computer scientists, b) programming skills, and c) access to electronic computing devices. To diminish these challenges, a problem solving and design approach has been recommended to teach computing concepts and principles through CT education (Guzdial, 2008), but this has yet to produce ways to separate CT from programming and the use of electronic devices. In our view, the lack of such separation has precluded us from capturing the true essence of CT, which could have helped narrow down the above list of CT skills to a smaller and more fundamental set of cognitive competencies that can be more easily taught at the K-12 level. Programming electronic devices may be a central tool for computer scientists, but there are non-programming computational tools available to and used by non-CS scientists. Since the goal of the CT initiative is to bring computing to non-CS students, how non-CS scientists use computers may be the key to find ways in which computing is separated from programming. An obvious example is the computational modeling and simulation tools (CMSTs).

While modeling and simulation is associated with one of the most important CT skills, i.e., abstraction, it has not received due attention because of the concern, perhaps, that it would keep learners from more mainstream computing practices as hinted by Grove and Pea. Also, the attention given to abstraction in the CS community is again because of its importance in computer programming (Armoni, 2013). It is true that without abstraction most of the large-scale computer software, including operating systems, compilers, and TCP/IP network software, could not have been written so efficiently. In fact, a good programmer is expected to be so good at abstraction that she should be able to easily oscillate between different levels of abstraction depicted in Fig. 1. Yet, the sad truth is that undergraduate CS students barely move beyond language-specific (level 2) or algorithm-specific (level 3) biases. Reaching level 4 is important to transform appropriate algorithmic and programming skills into different application contexts, yet the teaching of programming itself does not seem to accomplish this (Armoni, 2013).

Dijkstra, an early pioneer in programming, regarded abstraction as the most vital activity of a competent programmer (Armoni, 2013). Other prominent CS educators also see it as one of the most important characteristics of CT (Wing, 2011). So, if modeling and simulation is being recognized to facilitate abstraction skills as noted by Grover & Pea (2013), then an important task to link CT skills to our thought process is to investigate cognitive aspects involved in the practice of modeling and simulation. The good news is that this

ISSN:2149-8504 (online)

task has been recently done and we now want to merge its findings (Yaşar, 2016) with concepts from relevant disciplines to build and examine a theoretical framework that can help us narrow down the CT skillset in a way that can be promoted via modeling and simulation tools readily available at K-12.

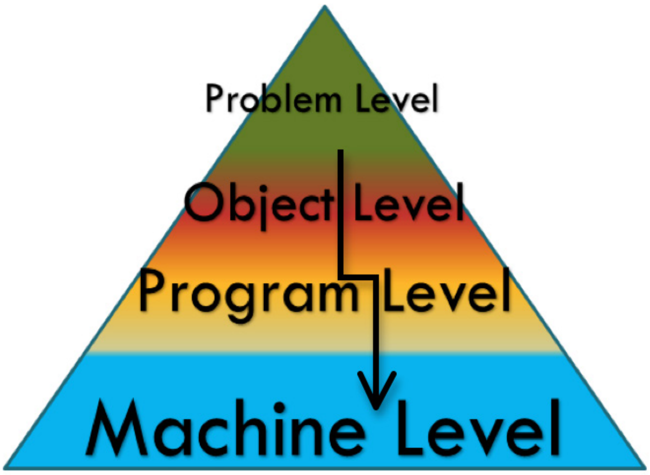


Figure 1. Multi-level abstraction in programming, From low to high: (1) machine-level, (2) program-level, (3) object-level, and (4) problem-level).

In the sections below, we introduce theoretical and empirical considerations from various fields – e.g., computing, neuroscience, education psychology, cognitive sciences and epistemology – as part of the foundation of our framework. These generally revolve around how knowledge is stored, retrieved, processed, and developed. At the core of our framework is the computational theory of mind (Montague, 2006), which basically claims that computational processing of information, regardless of the underlying device (electronic or biological), can facilitate and generate cognition. Assuming modeling and simulation to be a form of device-independent computation, as illustrated in Fig. 2, we will explore in the next section how such an approach might help us link electronic and biological computing. Then, we will present concepts from various fields to establish our framework. Finally, to test the framework we will describe a quasi-experimental design with more than 300 teachers using modeling tools in a diverse set of 15 secondary schools. Detailed findings of this case study have been presented earlier (Yaşar, et al. 2014, 2015, 2016), but their relevance to the essence of computational thinking is a new undertaking here. We will conclude by offering some recommendations and practical considerations for teachers or professional development program designers on how to integrate computational modeling and simulation into K-12 settings. The article will provide a link to a freely available database of curriculum modules and lesson plans teachers and other educators can use to design modeling-based educational materials for their professional development and K-12 classrooms.

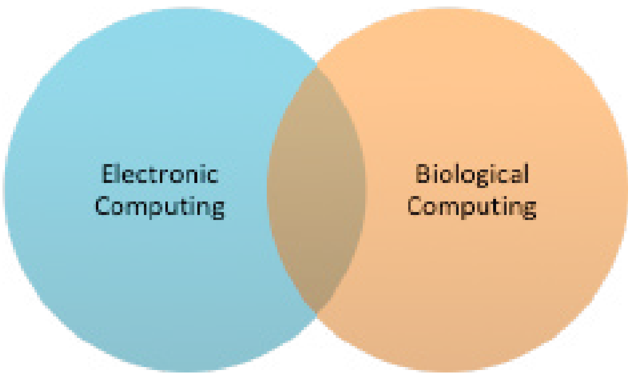


Figure 2. Device-independent elements of computing shown as an overlap of both electronic and biological computing

Device-Independent Computation

Seventy years ago, Alan Turing (1936), widely recognized as the founder of computer science, suggested that if thoughts (i.e., information) can be broken up into simple constructs and algorithmic steps, then machines can add, subtract or rearrange them as our brains do. Electronic machines have since successfully taken many complex and voluminous computations off our brains, and thus further supported the view of brain as a computational device.

Basically, there appears to be two root causes of similarities between electronic and biological computing patterns. One of them, as Turing alluded to, is the invariant behavior of information. That is, information constructs behave either by uniting to make bigger constructs or breaking down to smaller ones. Devices that can track and tally this computable behavior (addition and subtraction) are called computers, regardless of their underlying structure. This duality of basic computation manifests itself in other high level processes as we discuss it later.

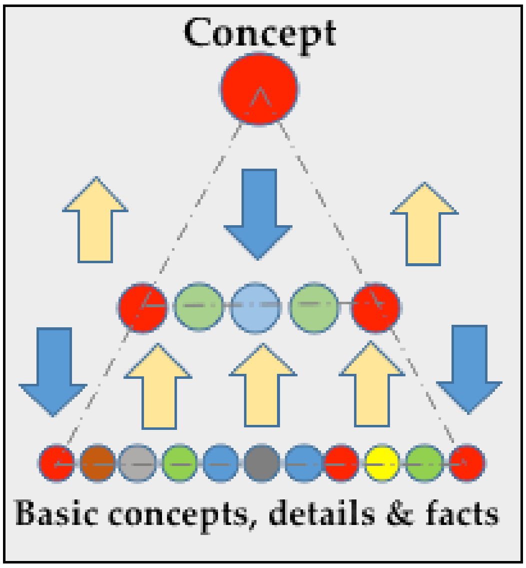


Figure 3. Distributive and associative ways of information storage, retrieval, and processing (Yaşar, 2017).

Another cause may be the control and use of electronic devices by biological computing agents. Our use of an electronic device can certainly reflect the way we use our own biological computing device (i.e., our mind). Their utilization, however, depends on how we use them. So far, we have used electronic devices in various ways, including programming (text-based and visual), office work, communication, visual arts, video games, virtual reality, modeling and simulations. These range from easy tasks (e.g., automation of repetitive and voluminous work) to complex tasks (e.g., solving systems of differential equations for which there is no analytic solution). In almost all these cases, electronic devices basically follow preloaded instructions and therefore offer almost none or little cognitive insight to us, except that virtual reality and computer simulations are known to have generated some insight in scientific research (Oden and Ghattas, 2014).

Modeling has been an important tool for scientific inquiry. As illustrated in Fig. 3, it is an iterative and cyclical process by which a previously constructed model (e.g., a concept or a theory) is analyzed (broken up) first and then synthesized (put together) – after testing, sorting, and updating – to either validate or change the original concept/theory. This cycle is repeated as resources permit until there is confidence in the revised model's validity. In recent years, computers have been very effective in conducting scientific research because they speed up the model building and testing of different scenarios through simulations that provide quick feedback to researchers in order improve the initial model. The role of computational modeling and simulation

ISSN:2149-8504 (online)

tools in scientific and industrial research has been proven beyond doubt because of their accuracy of predicting observed phenomena and improving industrial products (e.g., engines, planes, and cars) and their ability to conduct studies that are impossible experimentally, and ability to conduct studies that are impossible to do experimentally due to size, access and cost (NSF Report, 2006). As a result, modeling and simulation is now regarded as a third pillar of doing science because it facilitates the deductive and inductive cycle of scientific thinking (Oden and Ghattas, 2014; PITAC Report, 2005). Furthermore, modeling and simulation has been found to support deductive and inductive approaches to teaching as briefly reviewed in the next section (Yaşar & Maliekal, 2014; Yaşar 2016). So, judging from its utilization in both scientific research and teaching, one might say that modeling and simulation is a common process through which electronic and biological devices could resonate. The following section will employ this process to explain in simple and understandable terms what we know today about how information gets stored, retrieved and processed by the brain.

Epistemological, Psychological, Neuroscience & Cognitive Aspects of Thinking & Learning

Confidence in our understanding of how the mind works has been hindered by the fact that it involves a delicate, inaccessible, and complicated organ, the brain. Yet, not being able to dig into the most basic level of knowledge, details, and facts did not stop humans from coming up with theories and conclusions. Many fields have their hands in the study of how learning takes place in the mind. Epistemologists study how we know what we know by questioning an observer's subjective view of an objective world. Cognitive, developmental, and educational psychologists conduct empirical research into how people perceive, remember, and think. They form theories of human development and how they can be used in education. Neuroscientists use imaging techniques to understand the brain mechanisms that take part in learning. At the same time, more contemporary sciences of cognition and computing now collectively form theories and models of the mind to study how computation generates cognition. In the sections below, we will review developments in each of these as they relate to our article. We will first introduce what we knew two centuries ago about thinking and learning from an epistemological point of view. Then, we will visit relevant concepts from educational psychology a century ago, followed by views from contemporary sciences of neuroscience and cognitive sciences. In our view, they all reinforce the same general pattern of how our mind stores, retrieves and processes information. This consistency, obviously, is what has encouraged us to propose a framework, which we will introduce later.

Epistemological method of acquiring knowledge: Started a thousand years ago by Alhazen's emphasis on collecting experimental data to test accuracy and reproducibility of proofs, the epistemological method of acquiring knowledge evolved into a more robust form through use of both experimentation and mathematics by Galileo in the 16th century (Morgan, 2007). While natural scientists laid a strong foundation in the 16th century for how to acquire knowledge through empirical observations, philosophers debated for two more centuries whether a scientist's subjective view of the world could be considered as true knowledge. The debate's epistemological framework was about: a) how knowledge is acquired, and b) what the sources of knowledge are (mind, body, or both). This debate actually has not ended yet, because theories on interdependencies of matter and mind, such as how perception shapes up our thoughts through sensory experience and how the matter's existence may have preceded the meaning and essence of life (i.e., existentialism), still continue to mediate between perception and reality, and between philosophy and science using contemporary knowledge in physical, cognitive, and computational sciences (Hawking, 1988; Brown et al., 2014; Montague, 2006).

Historically, there have been two opposing epistemological views, namely rationalism and empiricism. Empiricism claimed that the mind is a blank slate and that it acquires knowledge a posteriori through perception and experiences, and by putting together in a synthetic way related pieces of information. Knowledge acquired this way is not warranted because new experiences may later change its validity. This is none other than the bottom-up (inductive) process shown in Fig. 3. Rationalism, on the other hand, has historically claimed that knowledge is acquired a priori through innate concepts. Innate knowledge is warranted as truth, and decisions and conclusions can be derived from it in an analytic way using deductive reasoning. And, this is none other

ISSN:2149-8504 (online)

than the top-down (deductive) process shown in Fig. 3.

Immanuel Kant (1787) argued against the views of both rationalists and empiricists and created a bridge to lay the foundations of epistemology. He recognized what experience brings to mind as much as what mind itself brings to experience through structural representations. In applying mathematical, logical, and physical representations to study of nature, Kant considered that knowledge developed a posteriori through synthesis could become knowledge a priori later. Furthermore, according to him, a priori cognition of the scientist continues to evolve over the course of science's progress (Rockmore, 2011). The epistemological method Kant established more than two centuries ago has been the method by which scientific knowledge has evolved, although its dual (deductive/inductive) cycle of change has historically been rather on the order of a social timescale, not an individual timescale (Giere, 1993; Kuhn, 1962). Historically, once proven or validated, a hypothesis or an observation was revisited at a very slow pace, sometimes spanning generations, because of both limited resources (time, money, equipment, etc.) and the overwhelming number of other questions begging for an answer or proof. However, the growing scientific knowledge and the number of researchers tackling a problem as well as the increasing capacity of technology have all now shortened the timescale of scientific progress, making us realize that the deductive/inductive process is also happening cognitively at individual timescales. Concepts and theories, which were once considered true and valid, are now quickly being modified or eliminated.

Modeling and testing has been an important tool for scientific research for hundreds of years, although at a slower pace than it is today. In principle, it works exactly as articulated by Kant, and as illustrated as in Fig. 3. Scientists ideally start with a model of reality based on current research, facts, and information. They test the model's predictions against experiment. If results do not match, they, then break down the model deductively into its parts (sub models) to identify what needs to be tweaked. They retest the revised model through what-if scenarios by changing relevant parameters and characteristics of the sub models. By putting together inductively new findings and relationships among sub models, the initial model gets revised. This cycle of modeling, testing, what-if scenarios, synthesis, decision-making, and re-modeling is repeated while resources permit until there is confidence in the revised model's validity. As noted before, computers have recently accelerated this cycle because not only they speed up the model building and testing but also help conduct studies that are impossible experimentally due to size, access and cost.

Educational psychology of learning: Another historical theory that has gone over deaf ears was documented about a century ago by Lev Vygotsky (1930), a Soviet psychologist. Factual details in coursework are often overwhelming, causing frustration and withdrawal for some students. Yet, effortful learning is the key (Brown et al., 2014) and the learner needs to have an interest and necessary background, skills, and confidence to attempt and maintain such effort. Today, we still wonder what to do when some of these ingredients are missing. Vygotsky theorized that the learner can benefit from a little push from his environment (e.g., teachers, peers, parents, instructional pedagogy and technology, etc.) to engage in the process of developmental and effortful learning. Unbeknownst until two decades ago to the American K-12 education system, which puts more emphasis on social development and freedom of choice (Mooney, 2013), his theory suggested that pushing a learner to catch up with his peers was much more important than giving him freedom to choose between effort and withdrawal or between interest and indifference.

Vygotsky's theory basically points out to the benefits of an instructional approach that would employ a general simplistic framework from which instructors can introduce a topic and then move deeper gradually with more content after students gain a level of interest to help them endure the hardships of effortful, constructive, and inductive learning. Such an iterative and stepwise progression toward learning is consistent with the use of deductive and inductive approach of teaching, scaffolding, and the psychology of optimal learning experience, which all emphasize the importance of balancing challenges and abilities to attain an optimal flow of learning (Csikszentmihalyi, 1990).

ISSN:2149-8504 (online)

From educational psychology point of view, there are many advantages of using a combination of instructive (deductive) and constructive (inductive) approaches. The deductive approach to teaching entails the teacher introducing a new concept or theory to students by explaining it first, then showing an application or two of the theory or concept, and wrapping up the instruction by affording students an opportunity to apply the theory or concept by completing homework problems (Prince and Felder, 2006). The inductive approach to teaching by contrast, first presents students with a problem, a case, or data from an experiment. Students are then guided to explore underlying facts, issues and the like. As the culminating step, students are led to acquire on their own an understanding of the underlying concept or organizing principle. Empirical evidence suggests that the inductive approach to instruction is superior and that it fosters greater intellectual growth (Bransford et al., 2000; Donovan & Bransford, 2005), but it requires significantly more resources (time, curricular materials, equipment, etc.) from both the teacher and students. While each approach has its pros and cons, prudent educators should take advantage of both approaches of teaching, especially if they are trying to address the preconceptions and misconceptions student bring to the classroom (Bransford et al., 2000). As epistemologists noted long time ago, these two forms of learning are inseparable.

Neuroscience view of information storage and retrieval: More than half a century ago, Donald Hebb (1949), the father of neuropsychology, explained cognitive functions in terms of neural connections. Often referred to as "neurons that fire together wire together," neural patterns became the center of our understanding of cognitive processing. According to Hebb, information is stored into the memory in the form of a specific pattern of neurons placed on a pathway and fired together. Basically, the number and strength of neural pathways influence the storage and retrieval of information. While this view continues to dominate the field of neuroscience, latest developments turn all conventional ideas of learning upside down (Brown et al., 2014). Cognitive psychologists now claim that forgetting is good for learning because it forces the learner to use effort to cognitively engage and recall or reconstruct newly acquired concepts through different neural pathways or links that exists and are retrievable. So, the more links to associated concepts, the higher the chances of recalling the newly acquired concept when needed later. Furthermore, cognitive retrieval practices attempted at different times, settings, and contexts are good because every time the recall is attempted, it establishes more links that will help the remembering and learning.

Both the long-term storage and retrieval of information involve a synchronized distributed participation of neurons in related regions of the brain and neuroscientists see little or no distinction between the acts of storage-retrieval and the act of thinking (MacDonald, 2008). This new consolidated view of storage, retrieval, and processing is actually very much in tune with our model of how learning takes place through modeling and simulation process. Applying our model (Fig. 3), then, to translate what neuroscientists says about storage and retrieval of information (Brown et al., 2014), we can say that a memory or a newly learned concept can be a combination or outcome of previously formed memories and concepts, each of which might also involve another level of vast network of concepts and details mapped onto the brain's neural network in a hierarchical way. When new information arrives, it lights up all related cues, neurons and pathways in a distributive process that is similar to the top-down action in Fig. 3, where new concept is broken up into related pieces. By the same token, retrieving a memory is a reassembly of its original pattern of neurons and pathways in an associative process similar to the bottom-up action in Fig. 3.

To summarize, similar to the distributive (top-down) process of storage, the mind attempts to interpret (i.e., think deductively) every new concept and information that it encounters in terms of previously registered models - objects, faces, scenarios, etc. And, as it grows further, the relationships among registered information eventually lead to interplay of various combinations and scenarios of existing models that eventually end up clustering in an associative (bottom-up) fashion (i.e., thinking inductively) related details into conclusions, generalizations, and more inclusive models of information (Bransford et al., 2000). An example of this dual processing would be as follows. Infants initially store and register most of incoming information in the form of disparate patterns because of their newness and thus before the age of 10-12 months they do not grasp that

ISSN:2149-8504 (online)

items falling from their mouths still exist. But, as a result of first relating incoming information deductively to previously stored information and repeated experiences, and then conducting what-if scenarios (i.e., simulations), they eventually conclude inductively that the item has just fallen out of their reach (Mooney, 2013; Brown et al., 2014).

Cognitive science view of information processing: While the distributed structure of neurons and their connections (i.e., hardware) influence cognitive processing (i.e., software), the relationship between software (mind) and hardware (brain) is not a one-to-one relationship. According to computational theory of mind, our mind consists of a hierarchy of many patterns of information processing and, just as the case in electronic computing, these levels may range from basic computations to more complex functions (sequence or structure of instructions) and models (mental representations) of perceived reality and imaginary scenarios (Montague, 2006).

While computational theory of mind has played an important role to separate mind from brain, the effort to model the mind as a rational decision-making computational device has not fully captured all our mental representations, particularly emotions (Goleman, 2006). Artificial intelligence and neural networks may never be able to model the human brain no matter how fast electronic computers become unless we understand what intelligence is and how the human brain makes decisions without exhaustive evaluations of all possible scenarios (Hawkins, 2004). For example, the human mind is known for its energy-efficient operation, consuming as little electricity as a dim light bulb (20 Watts), while computational cognitive modeling and simulation of human brain is expected to need 106 times more electricity – equivalent to a nuclear power plant (Simon, 2016).

One wonders, then, what accounts for the energy efficiency of human brain? Neuropsychologists, as well as evolutionary biologists, point to some structural (hardware) interference by an autopilot limbic system (animal-like brain) to by-pass, simplify, or reduce more elaborate cognitive functions of an evolved neocortex (outer parts of the human brain). It almost appears that we are caught up between two competing brains, as illustrated by the top-down <—>bottom-up cycle in Fig. 3: one that wants to simplify things and one that wants to dig things deeper. Cognitive scientists have developed many similar dual-process theories to study the duality of mind (Sun, 2002). Typically, one of these processes is fast, effortless, automatic, inflexible, nonconscious, and less demanding of working memory, while the other is slow, effortful, controlled, conscious, flexible, and more demanding of working memory (Evans & Frankish, 2009).

Cognitive scientist Read Montague (2006) points to some non-structural (software) tendencies to account for our brain's energy-efficient operation. He suggests that concern for efficiency, as part of our survival, is a major driving factor. While this concern comes at the expense of being slow, noisy, and imprecise, it does assign value, cost, and goals to our thoughts, decisions and action, Montague argues. To assign these attributes, the mind carries out computations, builds models, and conducts hypothetical simulations of different scenarios. While evaluative and hypothetical simulations add additional overhead to decision-making by slowing it down, it still ends up saving it from undertaking more exhaustive computations. According to Montague, the tendency to make trade-offs between simplicity and complexity and between details and generalizations is actually the root driver of our intelligence, and why we have pushed ourselves to be smarter over time.

A model is a simplistic representation of complex and detailed reality, as illustrated in Figure 3. As we move up the pyramid, we inductively generalize the details by decontextualizing (abstracting) it's content. So, by modeling an object or some phenomena we end up with a wrapped package that masks its internal structure (details). An advantage of modeling is that it makes it possible to work with approximate, abstract, or average representations. It is a way of bringing closure to an unending investigation. The human brain uses modeling not only for mental representation of external objects but also for its own internal computations so it can compare their values and costs before making a decision. Many argue that the uniqueness of human intelligence comes from the modeling of thoughts through language and, as we all know, thinking via language constructs appears

ISSN:2149-8504 (online)

to be a major difference between humans and other animals. Jeff Hawkins (2004), a co-inventor of hand-held devices who is now teamed up with neuroscientists to design a mind-like device outside the realm of artificial intelligence or neural networks, claims that the crux of intelligence is the ability to make predictions through mental models. So, as we will see below, modeling and making predictions with them is a core computational process of thinking and learning.

Modeling and Simulation: A Process by Which Everything Seems to Form and Grow

The common pattern in all previous sections appears to be duality (e.g., associative/distributive or inductive/deductive) of information storage, retrieval, and processing by a mind. This is not a new claim as the presence of a dual mind has been discussed for a long time, but capturing its essence is what remains a challenge. Neuropsychologists and evolutionary biologists have come up with some structural (i.e., hardware) reasons to explain the efficiency and quickness with which human brain makes decisions. It involves two competing brains, not the right and the left hemispheres but rather an autopilot limbic system (animal-like brain) that structurally interferes a more evolved neocortex (outer parts of the human brain) to by-pass, simplify, or reduce its elaborate cognitive functions (Sun, 2002). Typically, one of these brains is fast, effortless, automatic, inflexible, nonconscious, and less demanding of working memory, while the other is slow, effortful, controlled, conscious, flexible, and more demanding of working memory.

Cognitive scientist Montague (2006), however, points to some non-structural (i.e., software) tendencies to account for our brain's dual behavior and its energy-efficient operation. He suggests that concern for efficiency, as part of our survival, is a major driving factor. While this concern comes at the expense of being slow, noisy, and imprecise, our brain does assign value, cost, and goals to thoughts, decisions and actions. Montague argues that the mind conducts computations, modeling, and simulations of different scenarios to assign these attributes. While these evaluative simulations add an overhead to decision-making by slowing it down, it still ends up saving it from undertaking more exhaustive computations. So, according to him, the tendency to make trade-offs between simplicity and complexity and between details and generalizations is the root driver of our intelligence and why we have pushed ourselves to be smarter over time. We are still not sure of whether the causes are structural or non-structural, but there appears to be enough evidence from psychology, neuroscience and cognitive sciences about duality of mind regarding its psychological behavior, information storage, retrieval, processing and reasoning, which altogether warrants a synthesizing effort as undertaken here.

We argue that heterogeneity is the essence of duality in computational processing because like other heterogeneous things such as physical matter, information constructs appear to behave in one of only two ways: they either unite to form bigger ones or break down to smaller ones (Yaşar, 2017). So, any computational device, be it electronic or biological, would have to compute by either adding or subtracting information constructs at the basic level. Heterogeneity gives quantifiable information an invariant property (i.e., computability) that constraints how a computational device would process it. So, processing (tallying) of information constructs by any computing device would involve a dichotomy, all the way from addition/subtraction type computation at the basic level to modeling/simulation type computation at higher levels. Both types of these computations are device-independent forms of associative/distributive processing.

But, then, some might wonder what the essence of heterogeneity itself is? It is interesting to note that the essence of heterogeneity is the computable (associative and distributive) behavior that it causes. In layman terms, this is akin to 'what you do is what makes you or destroys you.' So, the degree of heterogeneity, its growth and degradation (breakdown) all depends on its overall dynamics of computable actions. In a way, formation of heterogeneity, whatever the driver is, resembles the act of modeling because both seem to involve adding parts together to form a whole that masks its parts. In general, such action is either driven by external forces or by a collective "trial and error" process controllable by various conditions and rules of engagement— much like a simulation (Yaşar, 2017). In computational research and education, this process is driven by a researcher or a teacher. In cognition, it is driven by a self-aware brain, and in case of physical matter, it is driven by acting forces and fields. So, wherever we turn, we see modeling and simulation as a universal process by which everything

ISSN:2149-8504 (online)

behaves (Yaşar, 2015).

Philosophers and psychologists have been studying the parts-whole dynamics since Plato (Harte, 2002). The ancient saying of "a whole is greater than the sum of its parts" arguably by Aristotle as well as a more modern version of it "a whole is other than the sum of its parts" by the Gestalt psychologist Kurt Koffka (1935) indicate that a union (whole) of parts may have properties not seen in its parts. Part-whole relations continue to occupy researchers' minds such as Findlay & Thagard (2012) who offer many examples from natural and social sciences in their recent paper. For example, a human body is functionally different than its parts; so is an atom or a cell. Another example that is relevant to our subject is that the union of math, computing, and sciences, in the way computational modeling and simulation brings them together, gives rise to a new kind of (deductive/inductive) pedagogy that did not exist in any of these individual subject domains. However, together as a union, they give rise to a computational pedagogy (Yaşar and Maliekal, 2014) that has recently been instrumental to develop of a computational pedagogical content knowledge (CPACK) framework for teacher preparation, as shown in Fig. 4 (Yaşar et.al., 2016). We will later return to the relevance of CPACK in the final section of this article to describe a quasi-experimental study used in the empirical examination of our cognitive framework.

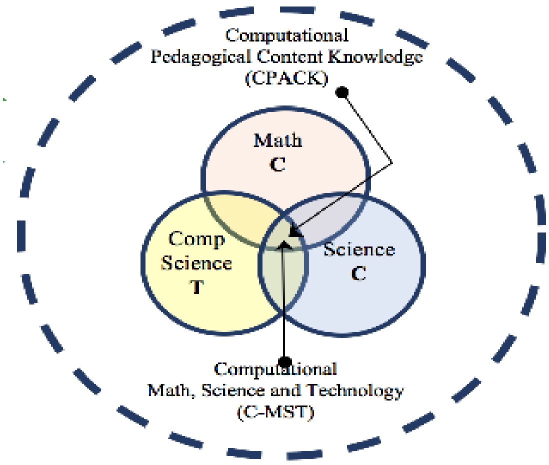


Figure 4. CPACK framework. Computational pedagogy is an inherent outcome of computing, math, science and technology integration

The Essence of Computational Thinking

Our framework is based on epistemological method of Kant (1787), computational theory of Turing (1936), and neuropsychological view of Hebb (1949). All have been around for a long time, but when merged with the latest work on computational pedagogy (Yaşar and Maliekal, 2014; Yaşar, 2016) for a new synthesis, we arrive at an interdisciplinary framework to describe in lay terms what computational thinking is and how cognitive functions are shaped up by computation. The previous sections were all necessary for our discussion to establish our cognitive framework, as they were not a mere repetition of the concepts found in the literature.

Accordingly, we argue that all quantifiable (distinct) things, such as matter and information, behave computationally (Montague, 2006) because they either unite (i.e., addition) or separate (i.e., subtraction) (Yaşar, 2017). We are surrounded by an environment that is flooded by quantifiable things, including matter and information as shown in Fig. 5. Since information is released from the matter's interaction with each other, the computable nature of information may merely reflect quantifiable behavior of physical matter. Or, its quantifiable behavior could be simply due to its own inherent heterogeneous nature. In any case, one can suggest heterogeneity is essential for dynamics to occur and be detected, because in a homogeneous environment all would be the same and not distinguishable.

If we fast-forward from the beginning of our universe to today, which started with a big explosion of homogeneous energy into heterogeneous units of matter and information, we might say that our brain's natural inclination to process information in an associative/distributive fashion, and to store and retrieve information in a scatter/gather way may all just be a manifestation of heterogeneity-caused duality engrained in the fabric of matter and information. This inclination may just be an evolutionary response, shaped up over many years, to optimize the handling of incoming sensory information whose quantifiable nature only resonates with distributive and associative operations. Accordingly, one can argue that associative processing of information by a computational mind is the essence of inductive reasoning – through which details are put together, focus is placed on general patterns, and priority and importance are assigned to newly acquired information. Inductive reasoning (i.e., abstraction) helps us simplify, categorize, and register key information from sparse, noisy, and ambiguous data for quicker retrieval and processing (Bransford et al. 2000; Brown et al., 2014; Donovan & Bransford, 2005). By the same token, distributive processing of information appears to be the essence of deductive reasoning – through which a general concept is analyzed and broken down in terms of its possible constituencies and their applicability and validity. Deductive reasoning helps us decompose a complex issue by dividing (scattering) the complexity into smaller pieces and then attacking each one separately until a cumulative solution is found (gathered).

We conclude, then, associative (+) and distributive (-) way of processing, storing, and retrieval of information is the very essence of thinking that is generated or facilitated by a computational device. We put this dichotomy at the core of information processing by both electronic and biological computing devices as shown in Fig. 6. And, we expect it to carry itself up to higher level cognitive processes, such as deductive reasoning as a form of distributive processing of information, and inductive reasoning, as a form of associative processing of information. As illustrated before, iterative and cyclical usage of deductive and inductive reasoning is the foundation of conceptual change, a process by which we progress our learning. However, its utilization depends on the underlying device structure and the quality and quantity of the environmental input it receives. Although cognitive researchers have already demonstrated how various forms of information processing could lead to cognitive inferences and generalizations (inductive reasoning) (Tenenbaum et al., 2011; Langley, 2000; Yang, 2009), here we are not concerned about details of computation-to-cognition but rather how duality in fundamental computation could lead to duality in cognitive functions.

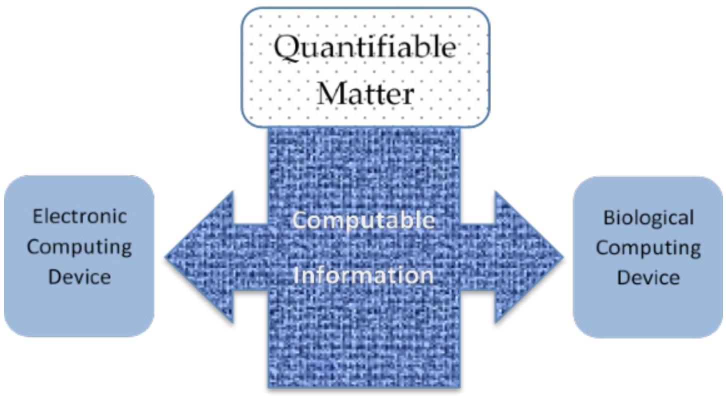


Figure 5. A view that quantifiable nature of information is simply a reflection of heterogeneous behavior of physical matter that emits such information.

The main tenet of our framework is that thinking is generated by a biological computing device and that it could also be equally facilitated, if not generated, by an electronic computing device. So, we equate computational thinking with ordinary thinking generated by a biological computing device and, in that sense, everyone, not just computer scientists, does computational thinking. Perhaps, we should distinguish between biological and electronic computational thinking to indicate that while each form of computing facilitates thinking processes, they also give rise to device-dependent processes. Then, as shown in Fig. 6, electronic CT

ISSN:2149-8504 (online)

would consist of biological CT as well as thinking caused by certain uses of electronic computing devices by a biological agent.

We may all be naturally inclined to employ associative and distributive thinking, however not all of us are equally aware of their importance, nor do we all practice and utilize them fully and equally in the form of deductive and inductive reasoning. Those who use them iteratively and cyclically would be experiencing conceptual change because the concept in question would be a target of decomposition and reconstruction (abstraction). If the concept stays the same, then its validity would be claimed, otherwise a conceptual change will have taken place. This is one of the foundations of scientific thinking (Dunbar & Klahr, 2012; Thagard, 2012). According to Paul Thagard, who specializes in philosophy and cognitive science, scientific thinking processes are no different than those used in everyday living by non-scientists. What he meant is that their essence is the same, and that the difference comes from how these processes are used. As explained in Yaşar et el., (2017), scientific thinking and biological computational thinking use the same cognitive processes as ordinary thinking. The difference is that an ideal scientist is someone who uses her mind's capacity for associative/distributive processing of information in a more iterative, cyclical, consistent, methodological, and habitual way.

Electronic CT skills naturally build upon cognitive processes that both scientists and non-scientists use, as shown in Fig. 6's outer layer. What it adds to them differently would be anything that is tied to the use of an electronic computing device for problem solving. Some of those uses, as mentioned before, would still be common to biological CT because they reflect the thinking of biological computing agents who uses them. And, that is probably why scientists heavily use electronic devices for modeling and simulation, as such use is driven by their own deductive and inductive thinking.

Figure 6: A cognitive framework on the essence of electronic CT skillset in terms of biological CT skills

Of all the characteristics of the electronic CT skill set listed in the literature (Grover & Pea, 2013), the two fundamental ones that have a correspondence with biological CT, as we defined here, are abstraction and decomposition. Others mostly seem to be rather device-dependent skills. Learning scientists and cognitive researchers point to abstraction as an inductive process. An example from our daily lives is that most of us do not care to see how cooks prepare our meals because we do not want to get bogged down with that level of details. Those who do and visit restaurant kitchens soon abandon this behavior, but others who continue to operate at increasingly smaller level of details (the bottom level in Fig. 3) can hardly function in society due to the attention they are paying to details. This myopic view of the world often causes burdens such as delayed action, indecisiveness, or inaction as dramatized by Shakespeare through the Hamlet character. By the same token, decomposition is a deductive process, often used to divide (scatter) complexity of an issue at hand into smaller pieces and then attack each one separately until a cumulative solution is found (gathered). The famous "divide and conquer" phrase, supposedly by Napoleon, as well as 'many a little makes a mickle' by Benjamin Franklin all point to public awareness of the importance of the decomposition strategy.

If abstraction is considered the packing (modeling) of things, then decomposition is the unpacking and examination of its contents. We all live in a constant cycle of packing and unpacking of information based on our changing need for details and generalizations. This process is akin to the top-down <—>bottom-up cycle in Fig. 3. However, while everyone uses abstraction and decomposition, not all are equally aware of the importance of these two essential biological CT skills, nor are we all practicing and utilizing them fully and equally. They are also essential elements of the electronic CT skillset, as listed earlier, because of their use in programming and problem solving with electronic computers (Armoni, 2013). For example, abstraction is used to distribute the complexity of a code into seemingly independent layers and protocols in such a way to hide the details of how each layer does the requested service. Domain decomposition, on the other hand, is used in parallel computing to distribute the workload among multiple processors. CS educators wish that students would get a chance before college to improve these skills through curricular standards and CT practices.

Results From Use of Our CT Framework in Education

While modeling and simulation capacity was available only to a small group of scientists in national labs a few decades ago, a dramatic increase in access to and power of high performance computing and the drop in its cost in the past 20 years helped spread the use of CMSTs into the manufacturing industry and academic programs such as those described in Yaşar and Landau (2003). It was not until friendly versions of CMSTs were available for K-12 settings that a detailed and thorough empirical research was undertaken to measure their effectiveness on teaching and learning. We ran a 5-year (2003-2008) K-12 outreach program to follow learning theories and national recommendations of offering secondary school students an opportunity to learn science through modeling and simulation. However, what started as an outreach effort by practitioners slowly transformed into a qualitative and quantitative research study to document the impact on teaching and learning. Details of this outreach/research experimentation has been previously published (Yaşar et al., 2014, 2015, 2016). Here, we will briefly mention some of the findings that are relevant to our discussion.

Table 1.

A typical list of user-friendly modeling and computer simulation tools

Interactive Physics (IP): investigate physics concepts. *http://www.design-simulation.com/IP.*
AgentSheets: investigate biology concepts via games & simulations. *http://www.agentsheets.com.*
Geometer's Sketchpad (GSP): model geometrical concepts. *http://www.dynamicgeometry.com.*
Stella: investigate chemistry concepts via modeling of rate of change. *https://www.iseesystems.com*
Project Interactivate: online courseware for exploring STEM concepts. *http://www.shodor.org.*
Excel: constructs hands-on modeling & simulations using rate of change (*new = old + change).*
Scratch: a menu-driven language for creating games and simulations. *http://scratch.mit.edu.*
Python: An object-oriented language with simple and easy to use syntax. *http://www.python.org/.*

A multi-tier teacher-training program supported the use and testing of modeling and simulation tools (Table 1) in both regular classrooms and after school settings. Our hypothesis was that there is a positive relationship between teacher variables (knowledge and ability) and student outcomes (knowledge, ability, and interest). Three independent variables (technology, pedagogy, and training) were considered. Multi-year PD included 80 hours of technology knowledge (TK) training the 1st year, 80 hours of technological content knowledge (TCK) training in the 2nd year, and 40 hours of technological pedagogical content knowledge (TPACK) training in the 3rd year. Teachers received TK training in multiple tools but were offered TCK training

ISSN:2149-8504 (online)

to integrate their choice of tools with their content. While monetary and technology (laptops, smart boards, and software) support were offered, participation was voluntary. Studies of interdisciplinary TPACK (Mishra & Kohler, 2006; Kohler & Mishra, 2008) training on teaching and learning are relatively new but have been well documented (see www.tpack.org). Our focus has been rather on computational pedagogical content knowledge (CPACK; a subset of TPACK) development (Yaşar et al., 2016) and its cognitive framework (Yaşar, 2016). A brief description of the CPACK framework was introduced previously.

More than 300 in-service STEM teachers from 15 schools, including 13 secondary schools (grades 7-12) from an urban (Rochester City, NY) School District (RCSD) and a middle school and a high school from a suburban (Brighton Central, NY) School District (BCSD) took part in activities of this inititative, which included summer professional development for in-service teachers; pre-service courses on computational methods, modeling tools, and pedagogoy; technology and curriculum support for participating schools; project-based afterschool programs; and annual competitions for students. The interdisciplinary aspect of the study and the need for teacher motivation/customization to implement new technologies necessitated a quasi-experimental design with mixed-methods (Creswell, 2012), involving collection and analysis of qualitative data (such as interviews, activity logs, observations) to identify variables as well as to understand and triangulate the quantitative data (such as Likert-scaled surveys, artifacts, report cards, test scores, and standardized exams).

Annually, we had about 50 active teachers in the program who each taught approximately 100 students in a school year. Modeling software tools in Table 1 were made available to all participating teachers, along with supporting technologies such as laptops, LCD projectors, and electronic smartboards. These menu-driven, user-friendly, and non-programming tools allowed students to quickly set up and run a model using an intuitive user interface with no knowledge of equations, scientific laws, and programming or system commands. An after-school project-based challenge program provided students more time and freedom than a regular classroom setting to apply, test, and revise the constructed computational models. More than 80% of teachers surveyed annually indicated that they utilized modeling tools in either classroom instruction or special projects. More than 90% of teachers who used tools provided to them by the project agreed that using modeling tools in their classrooms significantly increased student engagement and made math and science concepts significantly more comprehensible. While science classes utilized technology less due to limited access and lack of science-related modeling examples, in instances where it was utilized, a deeper understanding of science topics was achieved, compared to math topics (83% vs. 76%). Professional evaluators triangulated teacher reports through their own classroom observations.

Student learning data from report cards and NY State exams were found to be consistent with the survey data provided by teachers. For example, Tables 2 through 5 show passing rates (>65/100) in NY State Regents Physics/Math Exams as well as graduation rates in four urban (RCSD) and one suburban (BCSD) high schools with more than 30% of its math and science teacher workforce trained by the initiative. Student responses, except one case with a small sample size, from each school point out to a statistically significant ($0.01 < p < 0.05$) upward trend over the five-year study during which teachers were supported through summer and academic-year workshops, stipends, technology, and mentoring support. District averages are shown in Tables 4 and 5. RCSD passing rate average for NY State Grade 7-8 Math exam also improved: 10%→44%. Improvements over the baseline data were all statistically significant ($p<0.01$). No math teachers from BCSD middle school participated in the program because its baseline passing rate for NY Grade 8 Math was at 89%. Other known factors that may have affected statistics include RCSD's district re-organization into single secondary schools, State's redesign of its exams, and technological reform by these districts. A few control and target comparisons made in early phases of the project, before the control group was lost, consistently show favorable results. For example, a pair of teachers from the same high school taught properties of quadrilaterals in a math class. Class averages for the same unit test were 82.5 (size 24, using modeling tools) versus 49.5 (size 14, using conventional methods). Another study involved State's math exam scores of groups with similar sizes (25 students) in an annual challenge at three levels: Grade 7-8 Math: 64.0 vs. 58.6; Grade 9-10 Math-A: 60.26 vs. 49.54; Grade 11-12 Math-B: 71.9 vs. 55.6.

To circumvent curricular limitations, we offered an afterschool program through which participating teachers and student clubs organized a project-based annual competition. This program was also a way of doing an enriched case study with a qualitative component (e.g., interviews and observations) to explore the meaning of the quantitative trends/findings we learned in the student achievement data. Each year, top three team projects selected from school-based competitions were later submitted to a multi-school competition involving school districts. A rubric with good psychometric properties was developed and tested by computing and teaching experts. Project topics included addressing challenges of environmental issues and misconceptions. They allowed students enough time to progress at their own pace and resolve issues that they wanted to address.

Annually, more than 200 students had a full semester to develop 4-person team projects. Scoring rubric included problem statement, application of the model to a problem of interest, data analysis, teamwork, originality, electronic demonstration, and presentation of the results before a panel. Extra points were given for use of multiple tools, demonstrated understanding of computational, mathematical and scientific content, level of challenge, and knowledge and skills demonstrated beyond team's grade level. The incentives helped push students to go beyond initial job of model construction, playful experimentation, and introductory exposure to STEM concepts.

Table 2.
Passing rate at RCSD high schools

Regents Math-A	Baseline data		5 years later		p value
	Size	Rate	Size	Rate	
School 1	77	5%	427	62%	<0.01
School 2	319	13%	274	61%	<0.01
School 3	441	35%	384	75%	<0.01
School 4	43	21%	262	63%	<0.01

Table 3.
Passing rate at RCSD high schools

Regents Physics	Baseline data		5 years later		p value
	Size	Rate	Size	Rate	
School 1	21	0%	26	22%	<0.05
School 2	240	3%	162	31%	<0.01
School 3	11	0%	6	17%	<0.16
School 4	153	16%	81	26%	<0.05

Table 4.
Passing rate at BCSD high school

Regents Exam	Baseline data		5 years later		p value
	Size	Rate	Size	Rate	
Math-A	51	51%	295	97%	<0.01
Physics	123	52%	132	77%	<0.01
Diploma	259	84%	285	95%	<0.01

ISSN:2149-8504 (online)

Table 5.
Average passing rate at RCSD

Regents Exam	Baseline data		5 years later		p value
	Size	Rate	Size	Rate	
Math-A	880	23%	1347	65%	<0.01
Physics	425	7%	275	27%	<0.01
Diploma	1021	20%	1178	52%	<0.01

A case from this program has been reported by a group of these students in Yaşar et al., (2005, 2006). These papers offer a testimony of how high school students with no prior content knowledge slowly gained a deeper understanding of scientific and computing content. While they initially used tools whose operation they did not understand, they were eventually able to replicate the same simulations using a simple rate-of-change formula (new = old + change) with Excel. This is also consistent with themes extracted from qualitative data involving many team projects (n>300). Modeling examples from these projects are incorporated into lesson plans that are now freely available at http://digitalcommons.brockport.edu/cmst_institute/. They are being utilized at a rate of 80-100 downloads per day by educators around the world.

It appears that students' use of simple hands-on process of numerical integration via Excel helped them realize the virtue of decomposing a problem, as finer decomposition gave them more accurate answers (Yaşar and Maliekal, 2014). Because of limitations of Excel, the need for more accuracy, faster automation, and better control motivated them to seek other tools, including programming languages. A simple loop written in Python basically got them all they needed.

In hands-on modeling, the key is computation of change in the "new = old + change" equation. Since change is caused by laws of nature, it motivates students to learn about scientific laws that drive the change in nature. And, there are only a handful of them because whether they solve for harmonic motion of a pendulum, orbital motion of a planet, or launching of a rocket, change is caused by the same gravitational force. So, by knowing the formula for the force, they can get the change in velocity from acceleration (a=Force/mass) and compute the new velocity. This will give them the change of position (velocity x elapsed time), which they can use to get the new position. If one does this for many instances of time, then they would have a time-dependent profile of position and velocity. Because, solving these problems via a programming language could provide better control over decomposition, accuracy and automation, modeling and simulation is a great way to motivate students to learn knowledge of scientific laws and programming.

Our findings are consistent with a growing body of research that identifies computer simulation as an exemplar of inquiry-guided (inductive) learning through students' active and increasingly independent investigation of questions, problems and issues (Bell et al., 2008;Bell & Smetana, 2008; de Jong & van Joolingen 1998; Rutten et al. 2012; Smetana & Bell 2012; Wieman et al. 2008). Effectiveness of computer simulation in education is also well grounded in contemporary learning theories that recognize the role of abstract thinking and reflection in constructing knowledge and developing ideas and skills (Donovan & Bransford, 2005; Mooney, 2013).

Conclusion

We consider heterogeneity both as the cause and outcome of the dual (associative/distributive) behavior of stuff around us, including matter and information. While the physical matter has been showcasing this behavior through our sensory information for ages, we have only recently theorized that information could be considered in terms of quantifiable constructs. Such a theory by Alan Turing led to invention of electronic computing devices to imitate biological computing devices. Since then, electronic computing devices have grown in complexity and functionality to resemble biological ones. While we do not suggest that they are the same, they do process information in some common ways at the fundamental level. We argue that one of these common processes is modeling and simulation because it reflects device-independent associative and distributive aspects of information processing.

Our cognitive framework indicates that dual dynamics of information storage, retrieval, and processing by a computational mind is the very essence of thinking (or, computational thinking). While all utilize it in cognitive functioning, not everyone uses it as iteratively, consistently, frequently, and methodologically as scientists. In the past century, scientists have even invented electronic devices to help them automate computations involved in deductive and inductive reasoning of conceptual change process used in the scientific method. We have come to call these computations "modeling and simulation." Recent advances in technology has made real-time computer simulations possible, thereby effectively aiding the scientific progress in the past fifty years.

We infer from empirical data that modeling and simulation carries a constructivist pedagogy whose iterative and cyclical nature mirrors Kant's epistemological method represented in Fig. 3. Basically, modeling provides a general simplistic framework from which instructors can deductively introduce a topic without details, and then move deeper gradually with more content after students gain a level of interest to help them endure the hardships of effortful and constructive learning. This deductive approach takes away the threatening and boring aspect of STEM learning. Simulation, on the other hand, provides a dynamic medium to test the model's predictions, break it into its constitutive parts to run various what-if scenarios, make changes to them if necessary, and put pieces of the puzzle together inductively to come up with a revised model. It provides a dynamic medium for the learner to conduct scientific experiments in a friendly, playful, predictive, eventful, and interactive way to test hypothetical scenarios. This inductive process enables the learner to put pieces of the puzzle to come up with a revised model. Anyone who learns in this fashion would, in fact, be practicing the craft of scientists.

Pedagogical use of modeling and simulation in K-12 classrooms goes well beyond its benefits in math and science education. Students who experience learning in an iterative and cyclical process of deductive and inductive reasoning can transform such thinking to problem solving in computing as well. It can help students develop an understanding of abstraction and decomposition as well as an appreciation for computer programming. A deductive habit in programming practice could help programmers decompose a whole code into its smaller pieces and deal with each one separately until a cumulative solution is found. This is how large codes such as computer and network operating systems are divided up into a hierarchy of layers of varying functionality. Parallel computing is another example of decomposition. At the same time, an inductive habit in programming could have just an opposite benefit by pushing the programmer to see a larger picture and group together seemingly unrelated pieces of programming. Again, this is how complexity of large codes are divided into layers of growing simplicity.

If viewed more carefully from other fields such as philosophy, epistemology, physics, modeling can be quickly seen a more general and pervasive process than its role in electronic and biological computing. It appears to be rather a universal process by which all heterogeneous stuff seems to form and grow. So, as a universal process representing computable behavior of physical matter, it could help put computing at the heart of sciences and convince skeptics that computer science deals with natural phenomena, not artificial phenomena. Accordingly, we argue that it should be lifted beyond its recognition as a tool for scientific research.

While this study was originally motivated by an effort to capture the essence of computational thinking, one of its side benefits has been to link it to scientific thinking. Besides its ramifications for computing education, such a link can help clear up two major myths in science education by not only illustrating that scientific thinking is no different than ordinary thinking but also raising awareness that the scientific method is rather a two-way process, not a one-way linear process as perpetuated to this day by many textbooks and curricular resources. We hope that our perspective will help persuade public and young students that understanding and obtaining the mind of a scientist and an engineer is within their reach. Teaching young minds an awareness of computation-generated cognition as well as a cognitive habit of conceptual change could help them think like a scientist and be prepared to use electronic computing devices to further such thinking regardless of whether they work as a scientist or not.

Acknowledgement

Support by the National Science Foundation, through grants EHR 0226962, DRL 0410509, DRL 0540824, DRL 0733864, DRL 1614847, and DUE 1136332, is greatly appreciated.

References

Armoni, M. (2013) "On Teaching Abstraction to Computer Science Novices." J. Comp in Math & Science Teaching, 32(3); 265-284.

Bell, L. R., Gess-Newsome, J. and Luft, J. (2008) Technology in the Secondary Science Classroom. National Science Teachers Association (NSTA).

Bransford, J., Brown, A. and Cocking, R. (2000). How People Learn: Brain, Mind, Experience, and School. National Academy Press, Washington, D.C.

Brown, P. C., Roediger, H. L. and McDaniel, M. A. (2014) Make it Stick. The Belknap Press of Harvard.

Creswell, J. W. (2012) Educational Research. 4th Edition. Pearson Education, Inc.

Csikszentmihalyi, M. (1990). Flow: The Psychology of Optimal Experience. New York: Harper Collins.

de Jong, T., & Van Joolingen, W. R. (1998). "Scientific Discovery Learning with Computer Simulations of Conceptual Domains." Review of Educational Research, 68(2); 179-201.

Donovan, S. and Bransford, J. D. (2005). How Students Learn. The National Academies Press, Washington, D.C.

Dunbar, K. N., & Klahr, D. (2012). Scientific Thinking and Reasoning. In K. J. Holyoak and R. G. Morrison (Eds.), The Oxford Handbook of Thinking and Reasoning (pp. 701-718). London: Oxford University Press.

Evans, J. and Frankish, K. (2009). In Two Minds: Dual Processes and Beyond. Oxford University Press: Oxford.

Findlay, S. D. and Thagard, P. (2012). "How parts make up wholes." Frontiers in Physiology, 3, 455. doi: 10.3389/fphys.2012.00455.

Giere, R. N. (1993). Cognitive Models of Science. Minneapolis, MN: University of Minnesota Press.

Goleman, D. (2006). Emotional Intelligence. New York: Bantam Dell.

Grover, S. & Pea, R. (2013). Computational Thinking: A Review of the State of the Field." Educational Researcher, 42(1); 38-43.

Guzdial, Mark. (2008). Paving the way for computational thinking. Communications of the ACM 51(8); 25-27.

Harte, V. (2002). Plato on Parts and Whole: The Metaphysics of Structure. Oxford, NY: Oxford University Press.

Hawking, S. (1988). A Brief History of Time. Random House: New York.

Hawkins, J. (2004). On Intelligence. Times Books: New York.

Hebb, D. (1949). The Organization of Behavior. New York: Wiley & Sons.

Kant, I. (1787). The Critique of Pure Reason. Translated by J. M. D. Meiklejohn. eBook@Adelaide, The University of Adelaide Library, Australia.

Koehler, M. J., and Mishra, P. (2008). "Introducing TPCK," in Handbook of Technological Pedagogical Content Knowledge (TPCK) for Educators. Routledge Press: New York.

Koffka, K. (1935). Principles of Gestalt Psychology. New York: Harcourt, Brace, and World.

Kuhn, T. (1962). The Structure of Scientific Revolutions. Chicago: Univ. of Chicago Press.

Langley, P. (2000). Computational support of scientific discovery. International Journal of Human-Computer Studies, 54, 393-410.

MacDonald, M. (2008) Your Brain: The Missing Manual. O'Reilly Media: Canada.

Mishra, P., Koehler, M. J. (2006). "Technological pedagogical content knowledge: A framework for integrating technology in teacher knowledge." Teachers College Record, 108 (6), 1017-1054.

Montague, R. (2006). How We Make Decisions. Plume Books: New York.

Mooney, C. G. (2013). An Introduction to Dewey, Montessori, Erikson, Piaget, and Vygotsky. St. Paul: Redleaf Press.

Morgan, M. H. (2007) Lost History: The Enduring Legacy of Muslim Scientists, Thinkers, and Artists. Washington D.C.: National Geographic Society.

National Research Council (NRC) Report (2012). A framework for K-12 science education. Washington, DC: National Academies Press.

National Science Foundation (NSF) Report (2006). Simulation-Based Engineering Science: Revolutionizing Engineering Science through Simulation. Washington, D.C.

Oden, T. and Ghattas, O. (2014). Computational Science: The "Third Pillar" of Science. The Academy of Medicine, Engineering & Science of Texas' (TAMEST's) Annual Conference January 16-17, 2014.

Papert, S. (1980). Mindstroms: Children, computers, and powerful ideas. New York: Basic Books.

President's Information Technology Advisory Committee (PITAC) Report (2005). Computational Science: Ensuring America's Competitiveness. Retrieved from http://www.nitrd.gov/pitac/reports/20050609_computational/computational.pdf.

Prince, M. J. and Felder, R. M. 2006. "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases." J. Engr. Education, 95 (2); 123-138.

Repenning, A. (2012). Programming Goes Back to School. Comm. of the ACM, 55(5), 35-37.

Rockmore, T. (2011). Kant and Phenomenology. Chicago: The University of Chicago Press.

Rutten, N., van Joolingen, R., and van der Veen. (2012). The Learning Effects of Computer Simulations in Science Education. Computer & Education, 58; 136-153.

Simon, H. (2016). Supercomputers and Super-intelligence. 17th SIAM Conference on Parallel Processing for Scientific Computing, Paris, April 12 – 15, 2016.

Smetana, L. K. and Bell, R. L. (2012). Computer Simulations to Support Science Instruction and Learning: A critical review of the literature. Int. J. Science Education, 34 (9); 1337-1370.

Sun, R. (2002). Duality of mind: A bottom-up approach towards cognition. Mahwah, NJ: Lawrence Erlbaum Associates.

Tenenbaum, J. B., Kemp, C., Griffiths, T. L. & Goodman, N. D. (2011). How to Grow a Mind: Statistics, Structure, and Abstraction. Science, 331, 1279-1285.

ISSN:2149-8504 (online)

Thagard, P. (2012). The Cognitive Science of Science. Cambridge, MA: The MIT Press.

Turing, A.M. (1936). On Computable Numbers, with an Application to the Entscheidungs problem. Proceedings of the London Mathematical Society. 2 (1937) 42: 230–265.

Vosniadou, S. (2013). International Handbook of Research on Conceptual Change. 2nd Edition. New York and London: Routledge.

Vygotsky, L. S. (1930). Mind in society: The development of higher psychological processes. Cambridge, MA: Harvard University Press.

Wieman, C. E., Adams, W. K. and Perkins, K. K. (2008). PhET: Simulations That Enhance Learning. Science, 332, 682-83.

Wing, J. M. (2006). Computational Thinking. Comm. of the ACM, 49(3); 33-35.

Wing, J. M. (2011). Research notebook: Computational thinking – What and why? The Link Magazine. March 06, 2011.

Yang, Y. (2009). Target discovery from data mining approaches. Drug Discovery Today, 54 (3-4), 147-154.

Yaşar, O. & Maliekal, J. (2014). Computational Pedagogy. Comp. in Sci. & Eng., 16 (3), 78-88.

Yaşar, O. & Maliekal, J., Veronesi, P. and Little, L. (2014). An Interdisciplinary Approach to Professional Development of Math, Science & Technology Teachers. Comp. in Math & Sci. Teaching, 33 (3), 349-374.

Yaşar, O., Maliekal, J., Veronesi, P., Little, L. and Vattana, S. (2015) Computational Pedagogical Content Knowledge. In L. Liu and D. C. Gibson (Eds), Research Highlights in Technology and Teacher Education (pp. 79-87). ISBN: 978-1-939797-19-3.

Yaşar, O. (2015). A Universal Process: How Mind and Matter Seem to Work, Science Discovery. 3 (6), 76-81. doi: 10.11648/j.sd.20150306.16.

Yaşar, O. (2016). Cognitive Aspects of Computational Modeling & Simulation. J. Computational Science Education, 7 (1), 2-14.

Yaşar, O., Veronesi, P., Maliekal, J., Little, L., Vattana, S., and Yeter, I. (2016). Computational Pedagogy: Fostering A New Method of Teaching. Comp in Edu., 7 (3), 51-72.

Yaşar, O. (2017). Modeling & Simulation: How Everything Seems to Form and Grow. Comp. in Sci. & Eng., 19 (1), 74-78.

Yaşar, O., Maliekal, J., Veronesi, P. and Little, L. (2017). The essence of scientific and engineering thinking and tools to promote it. Proceedings of the American Society for Engineering Education Annual Conference, Columbus, OH, June 25-28.

Yaşar, P., Kashyap, S., & Roxanne, R. (2005). Mathematical and Computational Tools to Observe Kepler's Laws of Motion. MSPNET, http://hub.mspnet.org/index.cfm/14566.

Yaşar, P., Kashyap, S., and Taylor, C. (2006). Limitations of the Accuracy of Numerical Integration & Simulation Technology. MSPNET. http://hub.mspnet.org/index.cfm/14568.

ISSN:2149-8504 (online)

Journal of Research in STEM Education

Vol 2, No 1, July 2016, PP 39-58

RESEARCH REPORT

Exploring Student Understanding of Force and Motion Using a Simulation-Based Performance Assessment

Jessica Gale [a1], Jayma Koval[a], Stefanie Wind[b], Mike Ryan[a], Marion Usselman[a]

[a]*Georgia Institute of Technology, USA;* [b]*University of Alabama, USA*

Abstract: *Performance assessment (PA) has been increasingly advocated as a method for measuring students' conceptual understanding of scientific phenomena. In this study, we describe preliminary findings of a simulation-based PA utilized to measure 8th grade students' understanding of physical science concepts taught via an experimental problem-based curriculum, SLIDER (Science Learning Integrating Design Engineering and Robotics). In SLIDER, students use LEGO robotics to complete a series of investigations and engineering design challenges designed to deepen their understanding of key force and motion concepts (net force, acceleration, friction, balanced forces, and inertia). The simulation-based performance assessment consisted of 4 tasks in which students engaged with video simulations illustrating physical science concepts aligned to the SLIDER curriculum. The performance assessment was administered to a stratified sample of 8th grade students (N=24) in one school prior to and following implementation of the SLIDER curriculum. In addition to providing an illustration of the use of simulation-based performance assessment in the context of design-based implementation research (DBIR), the results of the study indicate preliminary evidence of student learning over the course of curriculum implementation.*

Keywords: Physical Science, Performance Assessment, Middle Grades Science

The need to produce more STEM graduates to maintain the national security and economic future of United The Standards for Educational and Psychological Testing (AERA, APA, & NCME, 2014) offer the following definition of performance assessments (PA): "assessments for which the test taker actually demonstrates the skills the test is intended to measure by doing tasks that require those skills" (p. 221). PA has been promoted as providing more direct or authentic measurement of student achievement than selected-response formats, such as multiple-choice assessments (Lane & Stone, 2006). PAs have been touted as essential indicators of student mastery of science content and skills that can serve as both formative and summative assessments (Lane & Stone, 2006). Lane and Stone argue, "to fully capture the essence of scientific inquiry requires the use of hands-on performance tasks that may be extended over a number of days" (p. 388). This perspective is echoed by the Committee on Developing Assessments of Science Proficiency in K-12 for the Next-Generation Science Standards (NGSS) recommendation that assessment tasks "should include—as a significant and visible aspect of the assessment—multiple, performance-based questions" (National Research Council, 2014, p. 7).

PA has been described as a useful method for assessing conceptual development and documenting students' alternative conceptions (i.e., misconceptions, naïve/intuitive theories). PA methods used in science education include tasks asking students to interact with physical stimuli and explain scientific phenomena (e.g. McCloskey, 1983) or draw pictures depicting their conceptual understanding (Vosniadou & Brewer, 1994). Despite considerable attention to PA, implementation is often limited by practical constraints related to time,

[1] Corresponding author. *Georgia Institute of Technology, Center for Education Integrating Science, Mathematics, and Computing (CEISMC), USA*, E-mail: jessica.gale@ceismc.gatech.edu

Gale, J., Koval, J., Wind, S., Ryan, M., & Usselman, M. (2016). Exploring student understanding of force and motion using a simulation-based performance assessment. *Journal of Research in STEM Education*, *2*(1), 39-58

ISSN:2149-8504 (online)

resources, and costs. Given these limitations, there are few examples of research utilizing performance assessments to measure science students' conceptual understanding over the course of curricular interventions.

Simulation-based Performance Assessment

The *Standards* note that simulation-based assessment formats may be especially appropriate in contexts where "actual task performance might be costly or dangerous" (AERA, APA, & NCME, 2014, p. 78). Similarly, the National Research Council (NRC) report Knowing What Students Know asserts "technology is making it possible to assess a much wider range of important cognitive competencies than was previously possible. Computer-enhanced assessments can aid in the assessment of problem-solving skills by presenting complex, realistic, open-ended problems…" (Pellegrino, Chudowsky, & Glaser, 2001, p. 266). Thus, simulation-based assessments offer a potential compromise, allowing for representation of scientific phenomena without the constraints and limitations inherent in performance assessments that involve student interaction with physical demonstrations or stimuli.

As efforts to enhance science education have employed innovative computer-based activities and simulations, researchers have begun to explore creative approaches to utilizing simulations for assessment (Thompson Tutwiler, Metcalf, Kamarainen, Grotzer, & Dede, 2016; White & Frederiksen, 2000). A number of projects have experimented with computer-based tasks intended to document and track learners' developing understandings or knowledge representations, such as through the creation of concept maps (O'Neil and Klein, 1997) or their development of persuasive arguments (Mislevy, Steinberg, Almond, Haertel, and Penuel, 2000). Similarly, the EcoXPT project (Thompson et al., 2016) has adopted a blended assessment strategy, with traditional assessments complemented by the analyses of log file data generated from student engagement within a multi-user virtual environment.

This study illustrates the use of a set of iteratively developed simulation-based performance assessment (PA) tasks within the context of a design-based implementation research (DBIR) project. Specifically, we describe data collected from the administration of four simulation-based PA tasks designed to assess 8th grade students' understanding of force and motion concepts following implementation of an experimental problem-based curriculum. Through illustrative examples and the analysis of student responses to PA tasks administered prior to and following the curriculum implementation, the study provides illustrative results from a sample of (N=24) of 8th grade students.

Methodology

This section describes the curricular context in which the assessment was conducted, the sample of students that participated in this study, and the simulation-based PA tasks.

Curricular Context: The SLIDER Project

SLIDER is an NSF-funded DRK-12 project examining the use of design and engineering, through LEGO robotics, in the context of 8th grade physical science classrooms. The SLIDER curriculum, which is comprised of two 5-week units, was iteratively developed over a three-year period within diverse school contexts, ranging from affluent, high-achieving suburban classrooms to relatively low-proficiency, low-income rural schools (Usselman & Ryan, 2014). SLIDER features contextualized design challenges intended to facilitated student learning of key physical science concepts. In SLIDER Unit 1, students apply their understanding of energy concepts (e.g. energy transfer, potential and kinetic energy) to engineer a solution to a traffic problem scenario - increased accidents at a dangerous intersection in a fictional town. SLIDER Unit 2 focuses on force and motion concepts (net force, balanced forces, acceleration, inertia) and culminates in a design challenge in which students use LEGO Mindstorms™ kits to design and test an automatic braking system for a robotic truck.

ISSN:2149-8504 (online)

For additional information about the SLIDER project and access to SLIDER curriculum materials visit https://slider.gatech.edu/.

Participants

The PA was administered to 24 eighth grade physical science students taught by a teacher implementing the SLIDER curriculum at a suburban middle school in the southeastern United States during the 2014-15 school year. Students were sampled from this particular teacher's classes because the teacher exhibited high fidelity of implementation of the curriculum relative to other SLIDER teachers. A mixed-methods sampling strategy was utilized in order to include students representing a range of achievement levels (Teddlie & Yu, 2007). Sampling began with analysis of student performance on multiple-choice items in the SLIDER Unit 2 pre-assessment. Using the dichotomous Rasch model (see Engelhard, 2013) to estimate student achievement, students were classified into achievement-leveled groups based on performance on the SLIDER Unit 2 pre-assessment (high, medium, and low). The second stage of the sampling procedure utilized reputational case selection (Goetz & LeCompte, 1984). The teacher was presented with a matrix of student names grouped by class period and achievement level and asked to recommend 24 students (eight students from each achievement level column) who had consistent attendance and had actively participated in SLIDER activities. The teacher was not informed that the three columns in the matrix represented student grouping based on achievement.

The SLIDER Simulation-Based Performance Assessment Tasks

The project utilized a multilevel approach to assessment (Ruiz-Primo, Shavelson, Hamilton, Klein, 2002; Hickey & Zuiker, 2012) in order to investigate student understanding of force and motion concepts within the SLIDER curriculum. In this approach, a variety of assessments are used based on their proximity to the curriculum being implemented. Student work or artifacts generated through students' interaction with the curriculum are considered immediate assessments. Close assessments align with the specific content and activities within the curriculum. Proximal assessments measure the acquisition of knowledge and skills relevant to the curriculum, but the topics or context of the assessment tasks can be different. Distal assessments, such as standardized tests, typically represent state or national standards in a specific discipline. Accordingly, the PA tasks described below serve as a proximal assessment that complements a set of other immediate- and close-level assessments imbedded within the curriculum and additional relatively distal assessments including standardized multiple-choice items. As proximal-level assessments, the tasks presented problem-solving scenarios that aligned to the same physical science concepts as the curriculum but differed in terms of context and, in some cases, difficulty. For example, within the SLIDER curriculum, students are asked to reason about force and motion in the context of automobile collisions (e.g. trucks hitting cars). In the PA, students are asked to transfer the knowledge they learned through SLIDER to answer different types of questions in a different context (figures pushing or pulling boxes).

The PA instrument includes four tasks, developed in collaboration with the SLIDER curriculum team to assess student understanding of major concepts addressed within the curriculum: net force, acceleration, friction, balanced forces, and inertia. The tasks were developed by adapting simulations from the University of Boulder PhET Interactive simulations (available online at: https://phet.colorado.edu/). Video-editing software was used to create short video clips portraying the selected PhET simulations for each task. Each of the four PA tasks is described below. (See Gale, Wind, Koval, Dagosta, Ryan, and Usselman, 2016 for additional details about the development and administration of the PA tasks).

Task 1: Net Force. Task 1, depicted in Figure 1, asked students to describe the net force represented in three tug-of-war scenarios. The researcher introduced the task by explaining that the tug-of war in the task was between two teams, and that figures from each team would pull the rope to move the cart over to their side. Students were told to disregard friction, gravity and the force from the ground (e.g. normal force) and that they should only consider forces from the figures pulling the rope. The task proceeded with three scenarios in which students were shown illustrations and asked to indicate whether there was a net force (e.g. "If we have four people of equal strength on each side, will there be a net force when the tug-of-war begins?"). When students predicted that there would be a net force, they were shown two arrows, a large arrow and a small arrow, and asked to choose and place it the illustration to show the net force. Students then watched a video simulation of the scenario and compared the result to their prediction.

Scenario 1 *4 vs. 4*	
Scenario 2 *4 vs. 1*	
Scenario 3 *4 vs. 4*	

Figure 1. Task 1: Net Force

Task 2: An Object in Motion Task 2, depicted in Figure 2, assessed students' understanding of net force using a simulation in which a figure pushes a box along a surface that they are told has a medium amount of friction. The speed of the figure increases as it pushes the box until the point is reached where the figure can no longer keep up with the box and falls away. The box continues to move forward but the speed decreases and eventually the box comes to a complete stop. After viewing the full simulation video, the researcher plays the video a second time, pausing to ask students to identify and explain the direction of the net force at three time-points: when the figure pushed the box as the speed was increasing; after the figure fell away from the box and the speed was decreasing; and once the box came to a complete stop. At each time-point students were asked, "Is there a net force?" If they answered yes, they were asked to select either a large or a small arrow and place it on an illustration of the tug-of-war event to show the direction of the net force and to explain their placement of the arrow ("Tell me why you placed the arrow the way you did to describe the net force").

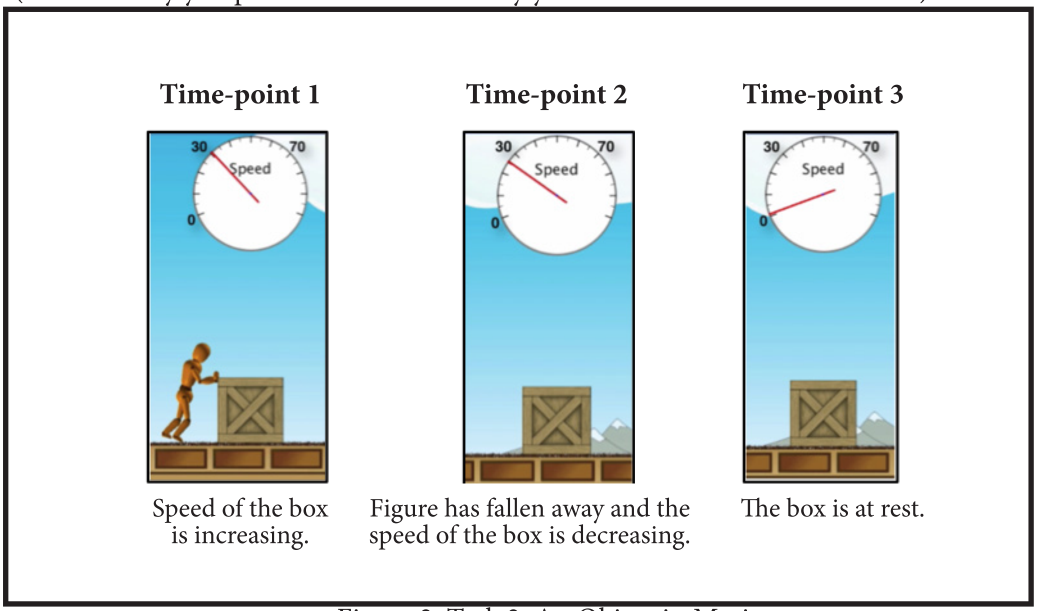


Figure 2. Task 2: An Object in Motion

Task 3: Balanced Forces. In Task 3, depicted in Figure 3, students considered a scenario in which they were asked to explain how a constant speed could be achieved. In the video simulation, they watched a figure push a box until it reached a speed of 70. Students learned that the figure was pushing with 250 N of applied force and the force of friction was 125 N. When the box reached the speed of 70, the researcher paused the video, presented a picture of the same moment and asked, "Let's say the figure wants to keep the speed at 70. What could the figure do to make that happen?" Additional probing questions were used, as necessary, to elicit student explanations. Specifically, researchers sought to determine whether students held the common misconception that balancing forces would cause the object to stop. Therefore, if students responded that the figure should push with more than 125N of force, the researcher probed with the question, "what do you think would happen if the figure pushed with 125N?"

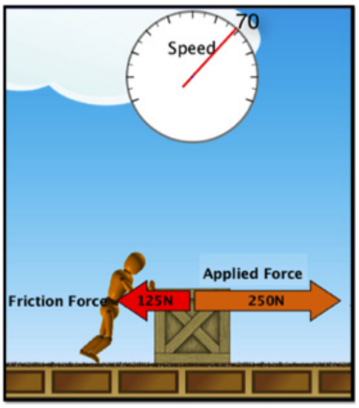


Figure 3. Task 3: Balanced Forces

Task 4: Inertia. Task 4, depicted in Figure 4, was designed to reveal students' understanding of inertia. First, students watched the figure push a box using 300N of force and use a stopwatch to measure how many seconds it took for the figure to push the box from a resting position to reach a speed of 70. In the second half of the simulation a second box was stacked on top of the first and the figure again used 300N of force to push the box from rest to a speed of 70. Before watching the simulation students were asked predict how long they thought it would take and why ("How many seconds do you think it will take for the boxes to reach a speed of 70…Why do you predict____ seconds?"). Students then used a stopwatch to measure how long it took for the figure to push two boxes to the target speed of 70. Students were then asked to explain why it took so much longer for the figure to push two boxes ("With one box, it took ____ seconds. With two boxes, it took ____ seconds. Why do you think that happened?") If students didn't mention inertia independently in their answer, they were prompted to describe the event in terms of inertia ("What can you tell me about inertia that might explain why this happened?").

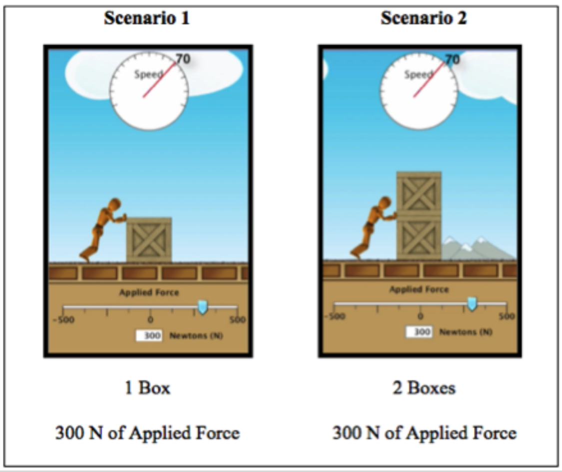


Figure 4. Task 4: Inertia

ISSN:2149-8504 (online)

Performance Task Administration

Task administration followed a protocol with a format similar to a semi-structured interview. The PA was conducted by the same member of the research team just prior to the implementation of SLIDER Unit 1 (Pre-PA) and approximately 3 months later (Post-PA), immediately following implementation of the SLIDER curriculum's second unit. This researcher had visited the participating classroom several times prior to the PA task administration, so students were accustomed to her presence and generally comfortable speaking with her. All performance assessment sessions were videotaped. A second researcher was present during PA administration to operate video recording equipment and take notes on student responses for each task. The PA took approximately 15 minutes per student for each administration and was conducted in a quiet area near the science classroom.

Data Analysis

Pre- and post- responses for each task were analyzed for each of the twenty-four participating students. Because student responses for PA Task 1 were limited to answering "yes" or "no" to the prompt "Is there a net force?", and to placing an arrow to indicate net force, Task 1 data was compiled from data sheets completed by researchers during task administration. Video recordings for tasks 2-4 were transcribed for analysis. Using the NVIVO software program, all student responses were coded by two members of the research team, including the researcher who administered the performance assessment. All student responses (both pre- and post-) were compiled in an NVIVO project file such that coders were blind to whether a student response was from the pre- or post-PA administration. Coding followed a protocol coding process (Saldana, 2013) wherein student responses were evaluated using a task-specific rubric iteratively developed by the research team. The rubric included two types of codes: holistic codes and explanation codes. *Holistic* codes, defined at four levels of understanding for each task, were utilized to describe the degree to which student responses were indicative of accurate conceptual understanding of targeted science concepts. Although rubrics were task specific, they generally defined a similar progression of conceptual understanding: "incorrect" responses indicative of alternative understandings inconsistent with accepted scientific understandings of force and motion concepts were coded at Level 1; "correct" responses consistent with accepted scientific understandings were coded at Level 2; and responses that were both "correct" and included an explanation that accurately referred to or applied a relevant force or motion concept were coded at Level 3. Following coding, differences between pre- and post rubric scores for each task were investigated using Wilcoxon signed-rank tests (Corder & Forman, 2014). Further analysis of student responses included the application of *Explanation* codes, which categorized the explanations and predictions students provided within the tasks and indicated whether students arrived at their ultimate responses independently or through follow-up questions from the researcher, which we refer to as "prompting". Task rubrics (see Appendix) were revised with input from the SLIDER research team following a first round of coding. Following a second round of coding, coder comparison queries indicated 94% agreement between coders across tasks. Remaining coding discrepancies were resolved through discussion between coders.

Results

This section presents results and illustrative examples for SLIDER's simulation-based performance assessment tasks, beginning with descriptive results for the introductory Task 1 and followed by results and illustrative examples of student responses for Tasks 2-4.

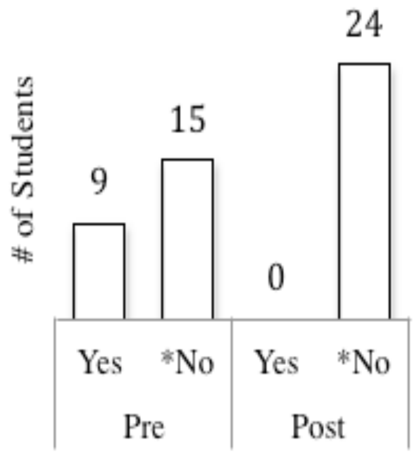
Task 1

Student responses to the Task 1 prompt, "Is there a net force?" and their ability to correctly place an arrow indicating the direction and magnitude of the net force, suggest subtle differences between pre-and post response patterns. As indicated in Figure 5, on the pre-PA, nine of the 24 students incorrectly stated that there was a net force in Scenario One. Asked to describe the net force, five of these students were unable to give a response or said "I don't know" and four students stated that the net force is "the same on each side", suggesting potential confusion between the vocabulary "net force" and "force". For Scenario Two, nearly all students responded correctly to both prompts at both pre- and post-PA. For Scenario Three, at both pre- and post-PA all students correctly affirmed the net force and correctly indicated the direction of the net force; however, there was an increase in the number of students who selected the small arrow to correctly indicate the magnitude of the net force from pre- to post-PA.

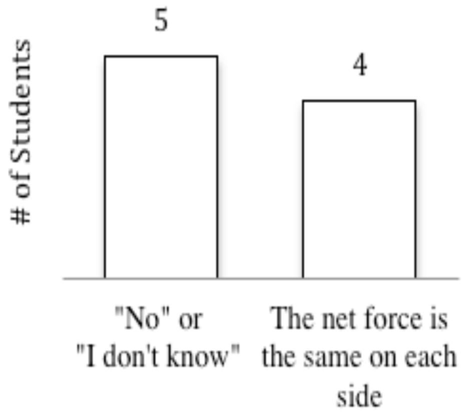
That even students who responded incorrectly on scenario one were able to correctly state whether there was a net force in scenarios two and three suggests that students who began the task with a lack of understanding of net force may have learned the basic concept over the course of the task. Given the simplicity of the task and that students were shown simulation videos illustrating the outcomes for each tug-of-war scenario after giving their response, it is also possible that students simply inferred the basic meaning of "net force" rather than developing an accurate understanding of the concept. Thus, "correct" answers to the yes/no questions in scenarios two and three do not necessarily indicate fully developed conceptual understanding.

ISSN:2149-8504 (online)

Scenario One

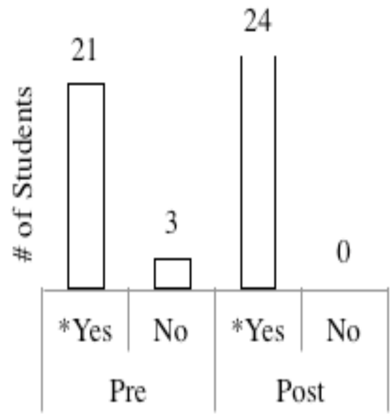


"Will there be a net force?"

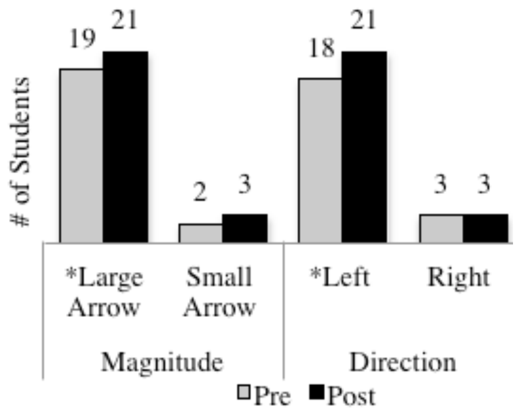


(If Yes)" Can you describe the net force."

Scenario Two

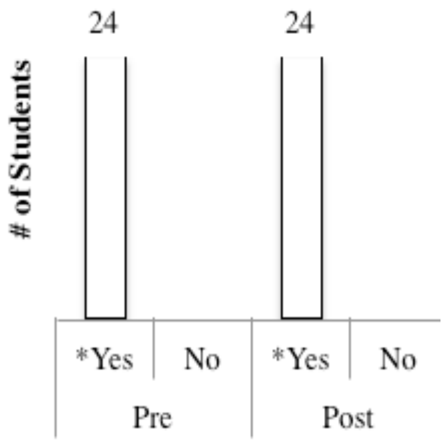


"Will there be a net force?"

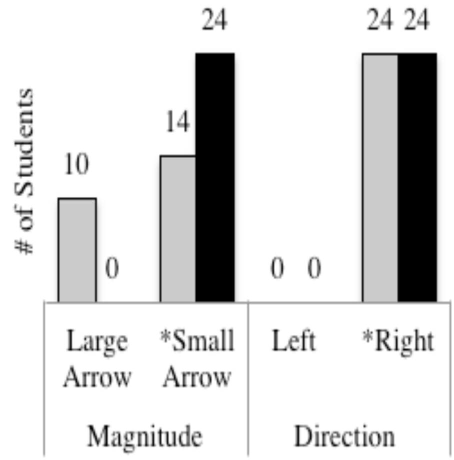


(If Yes) "Choose an arrow and place it to show the net force."

Scenario Three



"Will there be a net force?"



(If Yes) "Choose an arrow and place it to show the net force."

ISSN:2149-8504 (online)

In addition to assessing students' understanding of net force, Task 1 was intended to serve as an introduction to the simulation-based performance task format and provide a mastery experience for students presenting more conceptually difficult tasks that would require students to provide explanations of force and motion phenomena depicted in simulations. The ease with which students responded to the prompts suggests that Task 1 was successful in this regard.

Task 2

Recall that in Task 2, students viewed a simulation that depicted a box in various states of motion at three time points. Students were asked at each time point whether there was a net force acting on the box, to indicate the direction of the net force using an arrow, and to explain why they placed the arrow where they did to show the net force.

Figure 6 depicts student-level rubric scores at pre- and post-PA administrations. Prior to SLIDER implementation, 20 of the 24 students gave a Level 1 response, inaccurately stating whether there was a net force and/or indicating the incorrect direction of the net force. Relatively few students provided explanations that referred to applied force and/or friction (Level 2) or compared applied and frictional forces (Level 3). Although three of these students maintained this inaccurate response at post-PA, seventeen students provided scientifically accurate responses following SLIDER and the majority of these students (n=10) progressed from a Level 1 to a Level 3 response in which they not only correctly indicated the net force but also explained their response by explicitly discussing balanced forces or comparing the relevant applied and frictional forces within the simulation scenario. These patterns are consistent with Wilcoxon signed-rank tests showing statistically significant changes in rubric ratings between pre- and post-PA administrations for Task 2 ($Z = -3.93$, $p < .001$).

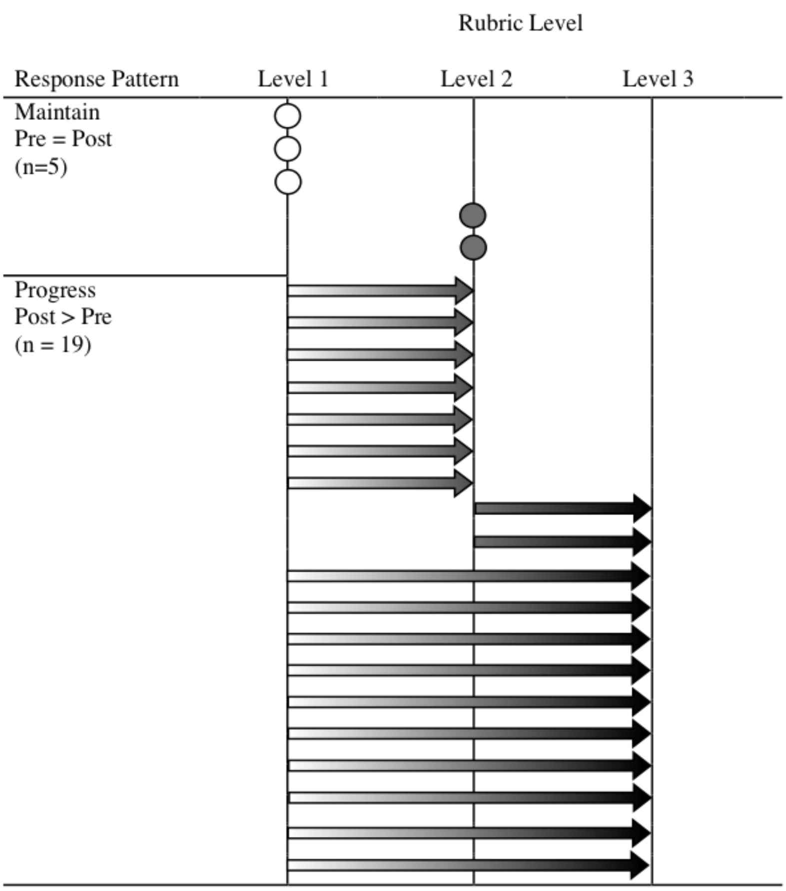


Figure 6. Task 2 Pre-Post Rubric Scores by Student.

Note: Dots represent unchanged rubric scores and arrows represent pre-post changes in rubric level scores for each student. See Appendix A for rubric level definitions.

Figure 7 illustrates the pattern of student responses when asked to explain their responses when the box was moving (Time-points 1 and 2) and when the box was at rest (Time-point 3). Note that because time-points 1 and 2 represent conceptually similar events (the box in motion), student responses at these two time-points were combined for analysis.

Taken together, student responses coded using the holistic and explanation rubrics illustrate a shift in student understanding of the targeted physical science concepts assessed by Task 2. This shift in understanding is further illustrated in the example presented in Table 1, in which the student provides a Level 1 response prior to SLIDER and a Level 3 response following curriculum implementation.

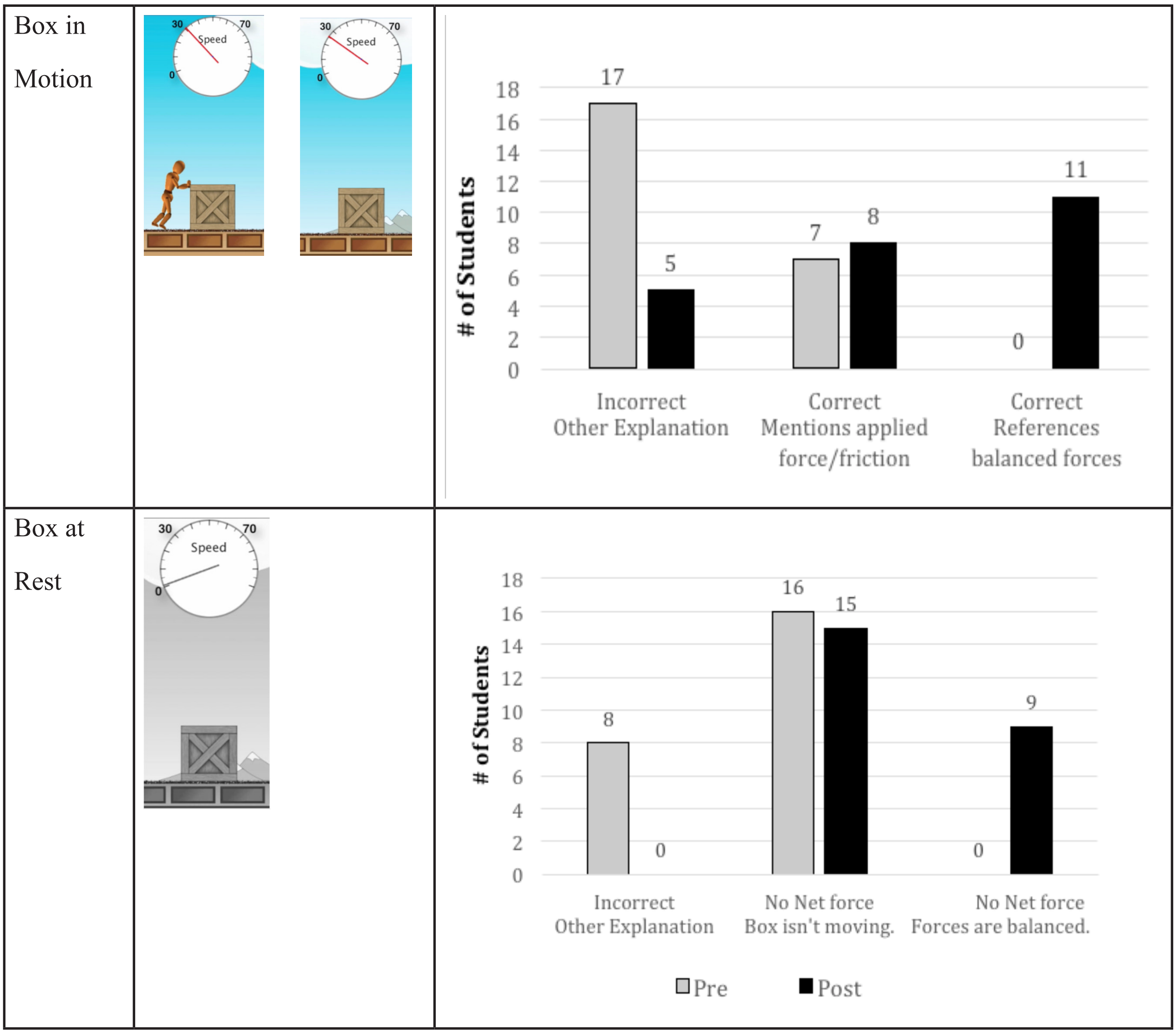


Figure 7. Task 2 Student Explanations

Table 1.
Task 2 Illustrative Example

Pre	Post
Time-point 1: R: Is there a net force acting on the box? S: Yes. R: Please place the arrow on the picture to show the net force. S: (Student places the arrow pointing to the right.) R: Tell me why you placed the arrow there? S: Because the man is pushing the box forward.	Time-point 1: R: Is there a net force acting on the box? S: Yes. R: Please place the arrow on the picture to show the net force. S: (Student places arrow pointing to the right.) R: Tell me why you placed the arrow there? S: Because the man is pushing the box and the amount of force he's using is greater than the amount of friction.
Time-point 2: R: …Is there a net force acting on the box? S: No. R: Tell me why. S: Because there's nothing moving the box in that direction.	Time-point 2: R: Is there a net force acting on the box? S: Yes. R: Please place the arrow on the picture to show the net force. S: (Student points arrow pointing to the left.) R: Tell me why you placed the arrow there? S: Because the man is no longer pushing it and the friction is greater than the force that is pushing it now.
Time-point 3: R: Is there a net force acting on the box? S: No. R: Tell me why. S: Because nothing is pushing the box in the right direction or the left direction.	Time-point 3: R: Is there a net force acting on the box? S: No. R: Tell me why. S: Because the box has stopped moving, there was no more friction affecting it and the box can't move forward because there is no one to push it forward.
[Response scored at Rubric Level 1]	[Response scored at Rubric Level 3]

Note: S = Student, R=Researcher.

Task 3

Recall that Task 3 asked students to reason about how a box being pushed with 250N of applied force could maintain a constant speed. Students answered the question "Let's say the figure wants to keep the speed at 70. What could the figure do to make that happen?" (See Figure 2). Figure 8 illustrates the distribution of students' scores on the holistic rubric for Task 3. These results suggest some development in students' understanding of how balanced forces operate when an object is in motion, with an increase in the number of students who explicitly referred to balanced forces when concluding that the figure should push the box with 125N of force to maintain its speed. At the same time, the persistence of incorrect Level 1 responses and the fact that four students exhibited a regressive response pattern, scoring lower on the holistic rubric at post-test than at pre-test, suggests that this was a particularly difficult task for many students. These patterns are consistent with Wilcoxon signed-rank tests showing a non-significant change in students' holistic rubric scores for Task 3.

ISSN:2149-8504 (online)

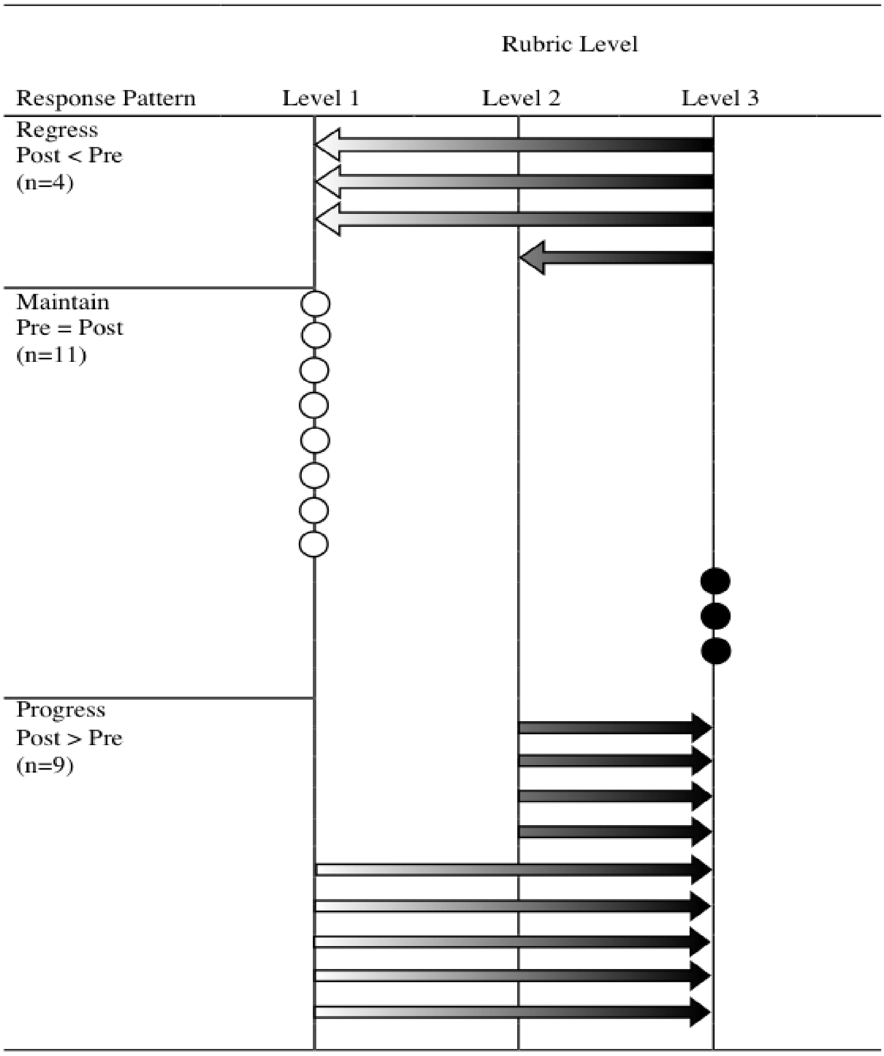


Figure 8. Task 3 Pre-Post Rubric Scores by Student.

Note: Dots represent unchanged rubric scores and arrows represent pre-post changes in rubric level scores for each student. See Appendix A for rubric level definitions.

Figure 9 presents the distribution of student responses to the Task 3 question "What could the figure do to keep the speed at 70?". At both administrations, students who provided an incorrect response were most likely to state that the figure should push with a force that is less than 250N but more than the frictional force of 125N. Further questioning revealed that a number of students providing this response (two at pre-PA and six at post-PA) held the misconception that if the forces were balanced such that the figure pushed with an applied force equal to the frictional force, the box would stop moving, a misconception that is well documented in the science education literature (AAAS, 2010). Figure 9 also illustrates the number of students who arrived at correct responses independently or through prompting at both the pre- and post- administrations of the PA. When students provided incorrect (Level 1) responses, researchers engaged students in further discussion in order to clarify or more fully reveal students' understanding. While the intention of these follow-up questions was not necessarily to lead students to change their answers but rather to clarify students' responses, we did find that, in some cases, students' responses in Task 3 evolved over the course of these discussions. A number of students at both administrations initially provided incorrect responses but arrived at the correct response through discussion; however, students were somewhat more likely to independently provide correct responses following the SLIDER curriculum.

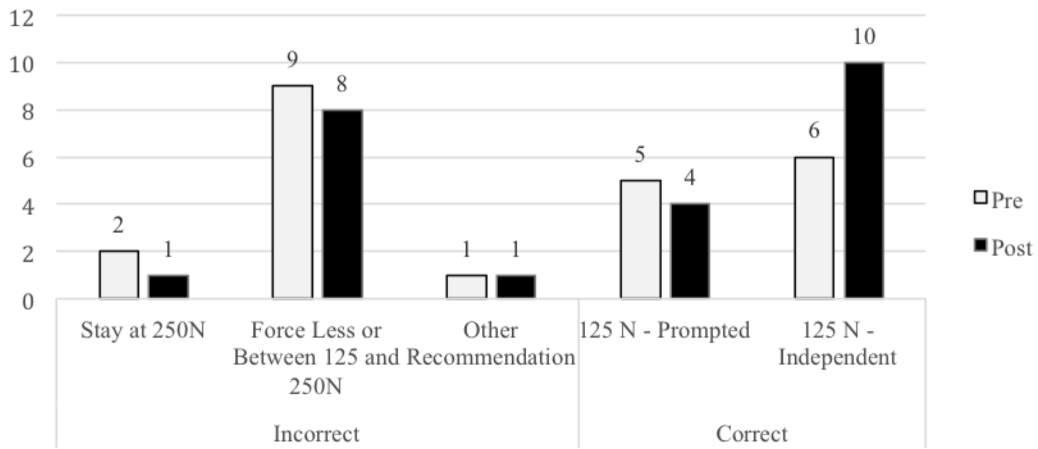


Figure 9. Student Responses to Task 3 Question: What could the figure do to keep speed at 70?

Table 2 presents an illustrative example of one students' Task 3. Prior to engaging with the SLIDER curriculum, the student initially gave a response approximating the scientifically accurate understanding that balancing the force with which the box is pushed and the force of friction would result in a constant speed. However, the student then changes his response, articulating the alternative understanding that balanced forces would cause the box to stop moving. Following SLIDER, the student seems to have revised his understanding to confirm his initial conception that balanced forces would produce a constant speed.

Table 2.

Task 3 Illustrative Example

Pre	Post
R: Let's say the figure wants to keep the speed at 70. What could the figure do to make that happen? S: They would lessen their force a little bit so that the forces would be equal. And then there wouldn't be a net force. But it would keep its speed….No. No. It would just make it go down. He would make his force go down a little, but not all the way to 125, because that would mean the box wouldn't be moving. So maybe to just about 200, or somewhere around there." [Scored at Rubric Level 1]	R: Let's say the figure wants to keep the speed at 70. What could the figure do to make that happen? S: It would cut its force in half because then that would balance out the forces and then it would just keep moving at a constant speed. [Scored at Rubric Level 3]

Note: S = Student, R = Researcher.

Task 4

Recall that Task 4 focused on the concept of inertia and asked students to predict and explain an increase in the time required for the figure to reach a certain speed when pushing two boxes versus one box. Figure 10 illustrates the distribution of students' scores on the holistic coding rubric for Task 4. These holistic coding results suggest a progression in students' understanding of inertia. All but one student provided responses indicating an understanding of inertia on the post-PA and there was an apparent shift in the extent to which students explicitly applied the concept of inertia to explain what they observed in the simulation. These patterns are consistent with Wilcoxon signed-rank tests showing statistically significant changes in rubric ratings between pre- and post-PA administrations for Task 4 ($Z = -3.72$, $p < .001$).

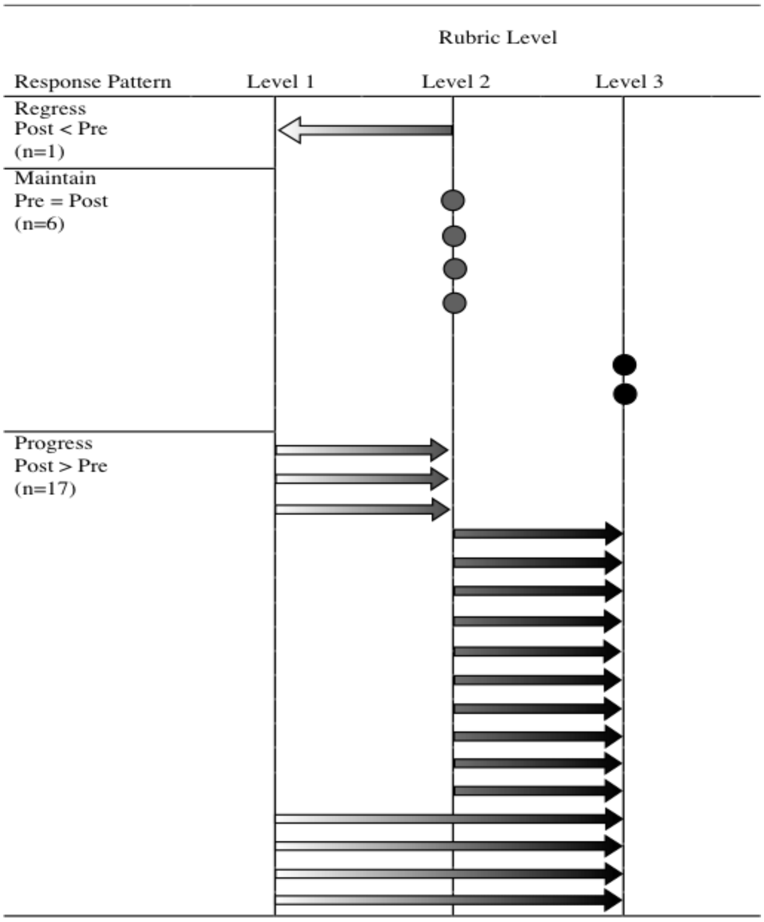


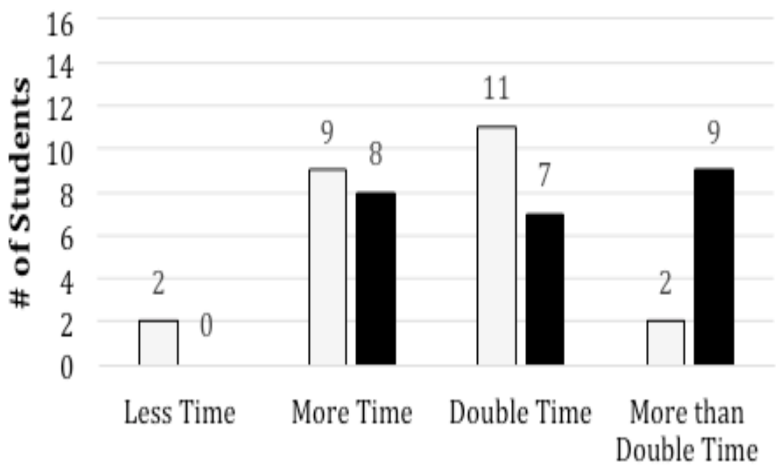
Figure 10. Task 4 Pre-Post Rubric Scores by Student.

Note: Dots represent unchanged rubric scores and arrows represent pre-post changes in rubric level scores for each student. See Appendix A for rubric level definitions

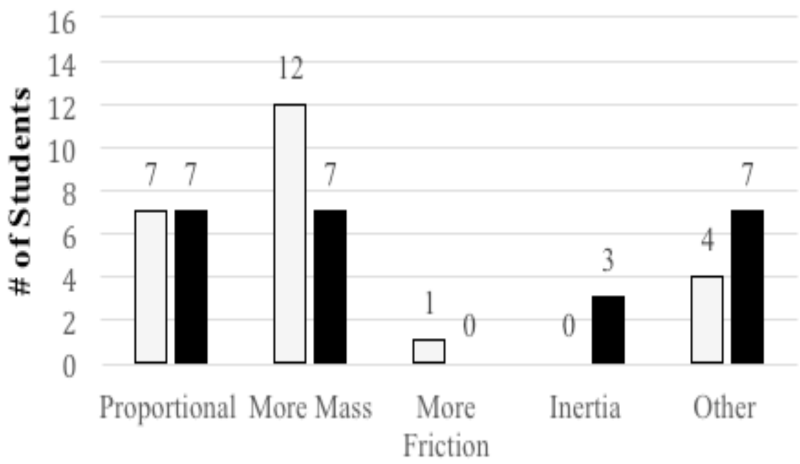
The pattern of student responses provided in Task 4, displayed in Figure 11, provides further evidence of a possible progression in student understanding of inertia. On the pre-PA, the majority of students claimed that it would take more time or twice the amount of time to push two boxes, explaining that this was either because the figure would simply be pushing more mass or because the time required to push the boxes would increase in proportion to the mass. On the pre-PA, only two students correctly predicted that pushing two boxes would take more than twice the time required to push one box. On the post-PA, students were nearly evenly split among predicting that pushing two boxes would require more than twice the amount of time, more time, or twice the amount of time. Although only three students provided explanations indicating their understanding of inertia on the pre-PA administration, the majority of students invoked inertia following SLIDER instruction, with six students independently using inertia to explain the phenomena and ten students doing so after prompting ("In your class, you learned about inertia. What can you tell me about inertia that might explain why this happened?").

ISSN:2149-8504 (online)

Prediction (Before simulation video):
How long do you predict it will take the figure to push 2 boxes?



Prediction Explanation:
Why do you think it will take ___ seconds?



Explanation
(After Simulation Video):
Why do you think that happened?

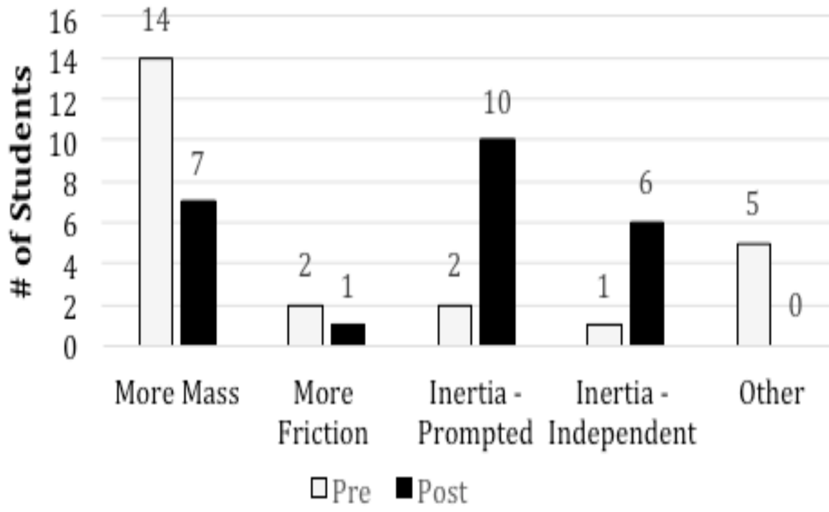


Figure 11. Task 4 Student Predictions and Explanations

ISSN:2149-8504 (online)

Table 3 provides an example of a student who provided a Level 1 response on the Pre-PA but earned a Level 3 score on the post-PA by spontaneously applying the concept of inertia both in his prediction and in his explanation of the simulation video.

Table 3.

Task 4 Illustrative Example

Pre	Post
R: When the figure was pushing one box, it took 8 seconds. Now there are two boxes. How many seconds do you think it will take for the boxes reach a speed of 70?	R: When the figure was pushing one box, it took 8 seconds. Now there are two boxes. How many seconds do you think it will take for the boxes reach a speed of 70?
S: 16 seconds.	S: (pause). 18.
R: Why do you predict ____16_____ seconds?	R: Why do you predict 18 seconds?
S: Because there are forces going the other way. So it's going to be harder to push it.	S: Because it's more than twice as much as the first one because I think it will take longer because its more…because it's harder to push something with more mass because the inertia is more, so you need more force.
R: (After Video) Why do you think this happened?	
S: Because…I don't know…because the force was greater than with one box. So with two boxes, it was greater force keeping…and you're not changing the force of the push. So if you want it to be faster, you'd have to increase the force of the push.	R: (After Video) Why do you think this happened? S: Because there is more mass, which leads to more inertia with the boxes the second time around and you need more force to push something with more inertia.
R: So it took longer because the force of the push wasn't enough?	[Scored at Rubric Level 3]
S: Yeah.	
R: Have you ever heard of inertia?	
S: No.	
[Scored at Rubric Level 1]	

Discussion

This study illustrates the potential of simulation-based PA as a method for exploring students' developing conceptions of force and motion. In their discussions of each of the four simulation-based PA tasks, students revealed the extent to which they held accurate conceptions of the force and motion concepts within the SLIDER curriculum. Implications of findings for each of the four simulation-based PA tasks are discussed below.

Task 1 was intended to be a relatively simple task used, in part, to help students become acclimated to the PA format and ease any apprehensions students may have about participating in the performance assessment interview. As expected, students found Task 1 to be simple. By the third tug-of-war scenario, all students were able to correctly determine whether there was a net force. While this result highlights the educative potential of simulation-based PAs, it also illustrates one of the complications of using PAs to measure changes in student understanding. As is the case with any assessment of pre-post learning, to the extent that the assessment itself enables students to deepen their understanding of a concept or provides feedback that enables students to provide increasingly correct answers over the course of task administration, researchers may be limited in drawing conclusions about the degree to which results indicate pre-post differences. This difficulty is compounded when performance tasks are designed to elicit simple responses rather than, as in Tasks 2-4, eliciting students' explanations of phenomena.

Task 2 asked students to reason about the net force within the context of a motion event - a box being pushed by a figure and eventually coming to a stop after the figure has stopped pushing the box. Again, students demonstrated more sophisticated understanding at post-PA than at the pre-PA administration. Following their experience with the SLIDER curriculum, all but five students were able to correctly identify the direction of the net force when the box was in motion (being pushed and slowing down) and all students correctly answered that the box at rest had a net force of zero. The explanations students provided also became more sophisticated, with students frequently discussing the balance of applied and frictional forces within the scenario.

In Task 3, students were told that the figure pushing a box wanted to maintain a constant speed, after which they were asked, "what could the figure do to make that happen?" As the SLIDER curriculum does not include activities that explicitly ask students to reason about balanced forces in this way, this task is an example of a proximal assessment (Ruiz-Primo, Shavelson, Hamilton, & Klein, 2001) that taps the relevant force and motion concepts but is not closely aligned to the curriculum. A greater number of students independently gave correct responses to this prompt after SLIDER instruction; however, this task remained relatively difficult, with ten students giving incorrect responses on the post-PA. Six of these students explicitly stated the alternative conception that if the figure pushed with an applied force equal to the frictional force the box would stop moving, a result that is consistent with previous conceptual development research documenting students' alternative understandings related to force and motion (McCloskey, 1983; Ioannides & 2001). Interestingly, this alternative conception appeared more commonly on the post-PA than on the pre-PA, where only two students responded that the box would stop if forces were balanced. This result may provide further evidence of the durability of this particular alternative conception and raises questions about whether and how the curriculum influences students' alternative conceptions in this area.

Task 4 represents another proximal assessment of students' developing understanding of physical science concepts. Within the SLIDER curriculum, students learn that inertia is an object's resistance to change in motion and they see a demonstration in which they make predictions and observations about the inertia of a stationary object (a dumpster being hit by a truck), but students are not asked to reason about inertia under different conditions as they are in Task 4 (i.e. one box vs. two boxes). Although this treatment of inertia within the curriculum is relatively brief, on the post-PA, the majority of students (n=16) explained the phenomena they observed in the Task 4 simulation video (i.e. dramatically increased time for the figure to push two boxes) by invoking inertia, with six students doing so spontaneously without prompting.

The results presented here lend support to the view that when it comes to revealing student understanding of difficult science concepts, simulation-based PAs may provide additional insight beyond what is obtained using traditional multiple-choice assessments, and more traditional PAs that do not involve interaction and discourse. As described above, there are a number of nuances we were able to discern through the analysis of students' responses that would not likely be evident through more traditional modes of assessment. For instance, by examining the discourse between student and researcher, we could distinguish students who spontaneously gave scientifically accurate responses from those who arrived at correct responses after engaging in further discussion with the researcher. Additionally, the study illustrates the particular benefits of simulation-based performance assessment, including the ability to simulate phenomena that would be difficult if not impossible to consistently present using physical materials. Although the time and resources invested in the development of simulation-based performance assessment tasks was considerable and may not be practical or appropriate for all assessment contexts, this approach holds promise for researchers and educators interested in gaining deeper understanding of student understanding of science concepts.

ISSN:2149-8504 (online)

These advantages notwithstanding, the study is not without its limitations. While efforts were made to select a sample representative of SLIDER students in the participating school, these results do not necessarily reflect the learning outcomes of all students who participated in the curriculum. A second limitation is the possibility of a test-retest bias. Given that the PA tasks and interview experience were likely quite novel, it is possible that students' pre-PA experience may have influenced performance on the post-PA. However, with the post-PA scheduled nearly three months following the pre-PA, we believe it is unlikely that students' remembered specific details or questions within the tasks. Additionally, with the exception of Task 1 where students watched videos illustrating the outcomes of the tug-of-war scenarios, our protocol intentionally did not provide students with "correct" answers to the PA task questions. Although the researcher who conducted the performance assessment interviews was present in the classroom prior to the pre-PA, she had spent much more time in the classroom conducting observations and focus groups with the participating students prior to the post-PA, so it is possible that students were more comfortable speaking with the researcher during their second PA experience.

Results from this study suggest a need for future research exploring innovative applications of simulation-based PA tasks. While the tasks utilized for this study required one-on-one interviews, one can envision similar tasks that could be administered online, perhaps for use by classroom teachers. Developing online simulation-based performance assessments that adequately probe student responses to generate useful assessment data presents a difficult but perhaps worthy challenge. Additionally, simulation-based PAs used in pre-post designs could be further developed by adding metacognitive items at post-PA in which students are presented with their previous responses and asked to reflect on changes in their understanding.

Conclusion

As performance assessment has emerged as a priority within the science education community, studies reporting on the administration and results of PAs will be essential. In addition to providing evidence of science learning outcomes of the SLIDER curriculum, this study illustrates the use of simulation-based PA as a promising method for gaining insight into student understanding of physical science concepts prior to and following curriculum implementation. As such, this work provides an opportunity to consider the advantages of PA over traditional modes of assessment. Similarly, this line of research raises important questions about the practical and methodological limitations of simulation-based performance assessment.

References

Alonzo, A. & Steedle, J. (2008). Developing and assessing a force and motion learning progression. Science Education, 93, 389-421.

American Association for the Advancement of Science [AAAS] Project 2061 (n.d.) [Pilot and field test data collected between 2006 and 2010]. Unpublished raw data.

American Educational Research Association, American Psychological Association, and National Council on Measurement in Education (AERA, APA, NCME). (2014). Standards for educational and psychological testing. Washington, DC: Author

Corder, G. W., & Foreman, D. I. (2014). Nonparametric statistics: A step-by-step approach. John Wiley & Sons.

Gale, J., Wind, S., Koval, J., Dagosta, J., Ryan, M., & Usselman, M. (2016). Simulation-based performance assessment: an innovative approach to exploring understanding of physical science concepts. International Journal of Science Education, 38(14), 2284-2302.

Engelhard, G., Jr. (2013). Invariant measurement: Using Rasch models in the social, behavioral, and health sciences. New York: Routledge.

Goetz, J. P. & LeCompte, M. D. (1984). Ethnography and qualitative design in educational research. New York: Academic Press.

ISSN:2149-8504 (online)

Hickey, D. T., & Zuiker, S. J. (2012). Multilevel assessment for discourse, understanding, and achievement. Journal of the Learning Sciences, 21(4), 522-582.

Ioannides, C., & Vosniadou, S. (2001). The changing meanings of force: From coherence to fragmentation. Cognitive Science Quarterly, 2(1), 5–62.

Lane, S., & Stone, C. (2006). Performance assessment. In R. Brennan (Ed.), Educational Measurement, Fourth Edition (pp. 387-431). Westport, CT: American Council on Education and Praeger.

McCloskey, M. (1983). Intuitive physics. Scientific American, 248(4), 114–122.

Mislevy, R. J., Steinberg, L. S., Almond, R. G., Haertel, G. D., & Penuel, W. R. (2001). Leverage Points for Improving Educational Assessment. CSE Technical Report.

National Research Council (NRC). (2014). Developing Assessments for the Next Generation Science Standards. Committee on Developing Assessments of Science Proficiency in K-12. Board on Testing and Assessment and Board on Science Education, J.W. Pellegrino, M.R. Wilson, J.A. Koenig, and A.S. Beatty (Eds.). Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

O'Neil Jr, H. F., & Klein, D. C. D. (1997). Feasibility of machine scoring of concept maps. Los Angeles: University of California. National Center for Research on Evaluation, Standards, and Student Testing (CRESST).

Pellegrino, J. W., Chudowsky, N., & Glaser, R. (Eds.). (2001). Knowing what students know: The science and design of educational assessment. National Academies Press.

Teddlie, C., & Yu, F. (2007). Mixed methods sampling: A typology with examples. Journal of Mixed Methods Research, 1(1), 77-100.

Thompson Tutwiler, Metcalf, Kamarainen, Grotzer, & Dede, (2016). A blended assessment strategy for EcoXPT: An experimentation-driven ecosystems science-based multiuser virtual environment. Paper presented at the Annual Conference of the American Educational Research Association, Washington D.C.

Usselman, M., & Ryan, M. (2014). SLIDER: Science learning integrating design, engineering and robotics. In Sneider, C. (Ed). The Go-To Guide for Engineering Curricula, Grades 6-8: Choosing and Using the Best Instructional Materials for Your Students. Corwin Press.

Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. Cognitive Science, 18, 123–183.

White, B. Y., & Frederiksen, J. R. (2000). Metacognitive facilitation: An approach to making scientific inquiry accessible to all. Inquiring into inquiry learning and teaching in science, 331-370.

ISSN:2149-8504 (online)

Appendix: Simulation-Based Performance Task Rubric

Task	Incorrect		Correct	
	Level 0	Level 1	Level 2	Level 3
Task 2	Student responds that they do not know and/or gives non-sensical responses.	Student incorrectly indicates whether there is a net force and/or the direction of the force (for any time point).	For every time point, student correctly indicates whether there is a net force and selects the correct arrows to represent the net force. (Yes,R; Yes, L: No, -)	For every time point, students correctly indicate whether there is a net force and select the correct arrows to represent the net force. (Yes,R; Yes, L: No, -) AND student compares applied vs. friction force or discusses balanced forces for any time point.
Task 3	Student responds that they do not know and/or gives non-sensical responses.	Student responds that to maintain speed, the figure should apply a force other than 125N. Task scored as Level 1 and recommendation as one of the following: Stay at 250N Force Between Greater than 250N	Student responds that the figure should apply 125N of force but does NOT refer to balanced forces in explanation.	Student responds that the figure should apply 125N of force so the forces are balanced.
			Explanation Codes: Stopping: Student states that if applied force =125N box will stop. Prompted: Student begins with Level 1 response but through questioning arrives at Level 2 or Level 3 response. Independent: Student independently states that figure should apply 125 N of force so the forces would be balanced.	
Task 4	Student responds that they do not know and/or gives non-sensical responses.	Student provides explanation of increased time that indicates alternative understanding of science concepts (force, motion, inertia, gravity, etc.)	Student explanation of increased time indicates accurate understanding of force and motion concepts but does not include inertia.	Student explanation of increased time indicates accurate understanding of inertia.

ISSN:2149-8504 (online)

Journal of Research in STEM Education

Vol 2, No 1, July 2016, PP 59-71

RESEARCH REPORT

STEM from the perspectives of engineering design and suggested tools and learning design

Yu-Liang Ting[a1]

[a]National Taiwan Normal University, Taipei, Taiwan

Abstract: *STEM is an educational concept about which little consensus has been reached as to what it is, and how it can be taught in schools. This study provides a snap shot of prominent contemporary research results contributing to better understanding of STEM and its implementation in education. In addition, this study tries to tackle an issue that school science has traditionally been built around well defined problems for learning purpose. As most real-world problems are ill-defined, this study proposes to implement the notion of STEM to help students acquire real-world problem-solving skills by engaging them in an engineering design process, in which students use the technology tools of graphic-based programming. The proposed learning practice is experiential task-based learning, in which students are forced to apply and acquire related science and mathematics knowledge during their engineering design process. It is hoped that related rationales and discussions will stimulates researchers and educators to adopt or tailor their own learning designs for the current generation of youngsters and promote the quality of teaching and learning in STEM.*

Keywords: Engineering design; Engineering design process; Experiential learning; Graphic-based programming tool

Introduction

STEM is an educational concept about which little consensus has been reached as to what it is, and how it can be taught in schools. Opinions vary as to whether it needs to be taught as a discrete subject or should be an approach to teaching component subjects, what progression should be followed in STEM education, and how STEM learning can be assessed (Pitt, 2009; Williams, 2011). Regarding each component in STEM, the S (Science), T (technology), and M (Mathematics) all have well-defined subject content and related courses in K-12 education. However, most school teachers are alien to the E, engineering. Katehi, Pearson, and Feder (2009) recommend that, in addition to developmentally appropriate knowledge and skills for mathematics, science, and technology, K-12 education should also focus on engineering design. Engineering addressed here concerns the type that utilizes knowledge in science and mathematics as well as the use of technological tools. Engineering or engineering design is about the design and creation of man-made products and a process for solving problems (Katehi, Pearson, & Feder, 2009). This design process or problem solving involves a trade-off, and takes into consideration what engineers call constraints. One constraint is the laws of nature, or science. Other constraints include such things as time, economy, politics, social concerns, available materials, environmental regulations, manufacturability, and repairability. Awareness of these constraints result from knowledge of science.

[1] *National Taiwan Normal University, Taipei, Taiwan*. E-mail: yting@ntnu.edu.tw

Ting, Y.-L (2016). STEM from the perspectives of engineering design and suggested tools and learning design. *Journal of Research in STEM Education, 2*(1), 59-71

ISSN:2149-8504 (online)

In fact, engineering design is different from science inquiry. Science inquiry, as defined by the National Science Education Standards (NSES p. 23), includes the activities through which students develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world and propose explanations based on the evidence derived from their work. Being used as a way of understanding science content, science inquiry helps students learn how to ask questions and use evidence to answer them. In the process of scientific inquiry learning, students learn to conduct an investigation and collect evidence from a variety of sources, develop an explanation from the data, and communicate and defend their conclusions.

School science has traditionally been built around well defined problems. Much of the curricula and teaching practices used in schools have been criticized because their academicism does not give students experience associated with real-world problems in situations where decisions are not clear cut (Fortus et al., 2004). Several researchers and organizations have recommended to restructure school science around real-world issues to help students develop the knowledge and skills necessary in a science and technology rich world (Blumenfeld et al., 1991; Fortus et al., 2004). It therefore has been asserted that engineering design process is a needed training in school because most real-world problems are ill-defined, lack required information, and do not have a known, correct nor best solution (Fortus et al., 2004). In the learning of engineering design, students are required to use and integrate their knowledge of both science and mathematics to develop a technological solution to a problem. This is not meant to claim a priority of engineering design over scientific inquiry. Both science and engineering are equally important. Scientists discover new knowledge by peering into the unknown, and engineers need to base on these discoveries to create functional produces (Carlson & Sullivan, 2004). Scientific inquiry is used to generate data for informing engineering design decisions. In education, engineering design can be used to provide contextualized opportunities for science learning (Katehi, Pearson, & Feder, 2009). Scientific investigation and engineering design can mutually reinforce each other (Katehi, Pearson, & Feder, 2009).

The engineering design manifests the science to be learned and the science that is learned directly impacts the modifications made to the design (Apedoe et al., 2008). The engineering design process does not only focus on having students apply the scientific knowledge that they have learned, but also support them to acquire and develop scientific knowledge in the context of designing artifacts (Fortus et al., 2005). That is, students learn the science concepts while they are engaged in design, rather than learning all the relevant concepts and then applying them to a design challenge. This elaboration not only reveals the relationship between scientific inquiry and engineering design, but also stands against the misconception of replacing scientific inquiry with engineering design, a mistake made by many school teachers in their early stage of implementing STEM.

Moreover, although the demand for engineers is increasing, the number of students pursuing careers in engineering is not (Hirsch et al., 2005). Apedoe et al. (2008) suggest that exposure to engineering design in the context of high school science is an effective way to encourage students to consider engineering as an important career option. Hirsch et al. (2005) established a program to provide school teachers with pre-engineering curriculum to better prepare students to enter engineering degree programs. The curriculum focused on pre-engineering skills and teachers learn to use instructional strategies that support students construct the connections between science, mathematics and engineering. Carlson and Sullivan (2004) also created an integrated learning program, in which students were introduced to the world of engineering and the iterative design process, including the use of technological tools and software. With the spirit of discovery learning spanning the K-16 continuum, the integrated program helps prepare and attract a student population whose diversity is representative of society at large (Carlson & Sullivan, 2004). A growing emphasis of K-16 engineering program is the preparation and guidance of middle- and high-school students towards the university engineering and technology program. In light of the above discussion, this study intended to employ the notion of STEM to help students construct scientific understanding and real-world problem-solving skills by engaging them in a proposed engineering design process.

STEM curriculum development

ISSN:2149-8504 (online)

The curriculum development in STEM requires teachers to set up an appropriate design task, in which two criteria are essential (Apedoe et al., 2008). Firstly, the task must be relevant to students' lives. Using a task that has personal relevance to students will increase student ownership and their excitement and interest in science and engineering design. Secondly, careful consideration must be given to the materials used in the design process, necessitating the use of tools for prototypes and working models. During the working process, the science materials need to be reliable and measured easily with these tools. Centered on an engineering design, there are two main types of STEM curriculum integration: content integration and context integration (Moore et al., 2014a; Moore et al., 2014b). Content integration focuses on the merging of content fields into a single curriculum in order to highlight over-arching learning goals, emerging from the subject content in each discipline and attributing to a related engineering design process. Context integration focuses on the content of one discipline and uses contexts from others to make the content more interesting, relevant, and challenging.

Content integration emphasizes on merging subject matter from multiple disciplines, and creates a curriculum that addresses content ideas from a combination of disciplines concurrently (Moore et al., 2014a). The curricular units explicitly contain learning objectives from individual STEM disciplines. For example, a socially relevant issue in improving quality of life, a STEM teacher might teach a unit that focuses on developing a coating to reduce frictional resistance of hip replacement joints to increase the lifespan of the product (Moore et al., 2014a). A stronger coating would increase the lifespan of hip replacements, reducing recipients' need for additional replacements. As another example, designing a method to clean up water in polluted ponds can incorporate a meaningful engineering design as part of the design method. This would introduce students to biological elements of clean water such as relationships within the ecosystem, and have students doing meaningful data analysis such as measuring pH, nitrogen, and phosphorous levels over time (Moore et al., 2014c), which allows the integration of content from multiple disciplines, including mathematics, chemistry, physics, biology, and biomedical engineering.

On the other hand, context integration accents one discipline while using a second to frame the lesson content for the purpose of creating meaning and relevance (Moore et al., 2014a). That is, context integrations places the focus of one discipline above others and use the secondary disciplines to provide a setting or situation that creates meaning and relevance for learning the primary content (Moore et al., 2014c). In these situations, STEM content integration is meant to reveal connections between disciplines and make tasks more meaningful and interesting for the students, but the curricula does not seek to address any learning objectives from the secondary disciplines (Moore et al., 2014b). For example, the context could be a company that is examining the reliability of tires to increase the vehicle safety. The context is engineering, but the unit focus is statistics in math, specifically Chi-square testing. Another example is counting pelican colonies from aerial photos to save pelican nests from damage. The context is engineering design with environmental issues, but the content is mathematics: unit area, perimeter, density, and early ideas of ratio and proportional reasoning (Moore et al., 2014c).

No matter the method of content or context integration, combining content from multiple disciplines in a meaningful way is not an easy task. It is important to ensure that the essential aspects of each subject content areas are not lost through the process of integration (Glancy et al., 2014). Williams (2011) proposed that, rather than integration, a more reasonable approach may be to develop interaction between STEM subjects by fostering cross-curricular links and the integrity of each subject remains respected. Interaction, rather than integration, involves providing links between the subjects when the rationale for such is clear, and is related to teachers' judgments about expected learning outcomes for students (Williams, 2011). Meanwhile, teachers must be willing to collaborate with each other and to believe that interactions between subjects will provide enhanced learning opportunities for their students. The impetus for meaningful STEM links in schools must be grass roots driven, and requires partnerships between teachers with a shared vision (Barlex, 2007; Williams, 2011).

Finally, it is important to recognize the requirements of STEM curricula (Moore et al., 2014a):

ISSN:2149-8504 (online)

1. the context must be relevant and motivating so students develop personal connections to the learning,
2. students must engage in the design process that develops students' creativity and higher-order thinking skills,
3. students should have opportunities to learn from failure and redesign,the main objectives of the lesson must include meaningful and important mathematics and/or science content,
4. the lessons that incorporate non-STEM content, such as reading or social studies, are suggested,
5. the lessons must incorporate and emphasize teamwork and communication.

When the STEM curricula follow the above requirements, it is expected that the learning practices will (1) increase student interest in STEM disciplines, (2) deepen student understanding of each discipline by contextualizing concepts, (3) broaden student understanding of STEM disciplines through exposure to socially and culturally relevant contexts, and (4) encourage student to enter STEM fields (Moore et al., 2014a).

Challenges in implementing engineering

Contrary to many common education practices, engineering does not assign learning to stand-alone subject domains. Engineers use their understanding of subject-area knowledge and associated skills to understand the problems and make use of tools to test solutions (Katehi et al., 2009). One of the fundamental aspects of engineering is mathematics, which provides a means to represent relationships and properties, and to develop models for predicting outcomes. Mathematics, science, and technology provide the content knowledge of the world, in which problems need to be resolved through engineering design processes. Many of the concepts introduced in the classroom present engineering opportunities (Mann et al., 2011). For example, students learn about the properties of materials, the motion of objects, the phenomena of light, the transfer of heat, and the conduction of electricity. In the engineering design for electricity and magnetism (Mann et al., 2011), students are required to use their knowledge of electrical circuits to create an electrical and/or magnetic invention that serves a purpose (e.g., alarm circuit and electromagnet). In this case, the science concepts and technology knowledge include: Power, Voltage, Resistance, Insulators, Circuits, and Magnetism. The required mathematical concepts is Algebra: application of a variety of formulas for basic circuit design and measurement. These statements reveal the interwoven relationships among subject domains in STEM.

Oftentimes, engineering is viewed wrongly as a separate entity, and teachers hesitate to add more to their curriculum. Some teachers experience anxiousness because they are unfamiliar with engineering concepts and careers, feel uncomfortable with open-ended problems when using the design process, or express concern with problems that do not have one right answer (Katehi et al., 2009; Mann et al., 2011). Claims of not having time and minimal knowledge, in addition to a perception of being overworked, result in the conclusion that engineering cannot be added into the curriculum (Douglas, Iversen, & Kalyandurg, 2004; Mann et al., 2011). It should also be clarified that integrating engineering into current teaching does not mean adding new curriculum. Engineering concepts could be demonstrated in all content areas but seldom are recognized as engineering.

It is therefore crucial to help teachers build up a descent understanding and attitude toward engineering design, which is not a new topic nor an un-precedent action to be added to students' existing over-loaded school work. People all naturally engage in design. People all use tools and materials purposefully when trying to suit their needs; thus, the capacity for design is a fundamental human aptitude (Fortus et al., 2004; Roberts, 1995). It is optimistic to expect that design-based activities have the potential to address a basic capability existent in all students (Fortus et al., 2004). Design is a particular, but representative, instance of real-world problem-solving, having no prescribed path leading from the required specifications to the final product design (Bucciarelli, 1994; Fortus et al., 2004). As the design product is the result of a wide range of value judgments, it is difficult to determine if a design product is the best solution to the requirements.

Engineering design process

Engineering design requires the linkage of (1) narrative discussion/description, (2) graphical explanations, (3) analytical calculations, and (4) physical creation, and the connection of math, science and technology can be present in the design processes (Wicklein, 2006). Hence, engineering design might serve to form motivating contexts to integrate the other three STEM disciplines (Katehi, Pearson, & Feder, 2009). The engineering design is meant to teach students that engineering is about organizing thoughts to form decision making for the purpose of developing better solutions and/or products for problems. The knowledge and skills associated with the process of engineering design do not depend on the engineering discipline (e.g., mechanical, electrical, civil, etc.) and/or engineering science (e.g., thermodynamics, statics, or mechanics) that a particular engineering problem is related to (Hynes et al., 2011). Design tasks entail developing critical thinking skills associated with engineering, technology, and science literacy.

The present study suggests using the technology tools of graphic-based programming for STEM in high schools. In general, graphical-based programming tools have a "low floor" (easy to get started) and a "high ceiling" (opportunities to create increasingly complex projects over time) (Lye & Koh, 2014; Papert, 1980; Resnick et al., 2009). Resnick et al. (2009) proposed one additional requirement of "wide walls", supporting many different types of projects so students with many different interests and backgrounds can all become engaged. For example, App Inventor is the invention of MIT and is hosted at the MIT Center for Mobile Learning (Morelli et al., 2015). App Inventor is a blocks-based visual programming language enabling people with little to no previous programming experience to create mobile Apps for Android devices. It aims to transform the complex language of text-based coding into visual, drag-and-drop building blocks. The simple graphical interface grants novices the ability to design and deploy a basic, fully functional App. The Inventor tool offers various modules, which can be selected via "drag and drop", and added to a screen. Those modules support data collection, including making use of the built-in sensors of smartphones. The data accessed by sensors can later be displayed on the mobile screen for science learning. For example, smartphones contain a large number of built-in sensors, such as accelerometers, gyroscopes, magnetic sensors and light detectors, which allow students to perform multiple science measurements in non-classroom settings. Smartphone accelerometers are a simple and easy way for students to collect data for the analysis of free fall (Kuhn & Vogt, 2013; Vogt & Kuhn, 2012). From a simple measurement like this, the students can understand the decrease/increase of weight when the elevator starts/stops the descent. What is more, students can obtain some interesting and scientific conclusions after a numerical analysis of the accelerometer measurement data (González et al. 2014). A more complex physical system is the physical pendulum, which can be experimentally studied using the acceleration and rotation (gyroscope) sensors available on smartphones (Monteiro et al., 2014). On an amusement park pendulum ride, the resulting data in the measurements of the radial and tangential acceleration and the angular velocity obtained with smartphone sensors can be graphed to assist in the creation of force diagrams to help students explain their physical sensations while on the ride (Monteiro et al., 2014; Vieyra & Vieyra, 2014). Students relate the graph of force diagrams to physical points on the ride and use Newton's laws of motion to explain and justify their physical sensations at those points on the ride. In this example, where the acceleration leads to forces experienced throughout the body, the connection between the experience of forces on and in the body and the mathematical description of motion helps students gain a deepened understanding of mechanics and its relevance outside the classroom (Pendrill & Rohlen, 2011).

This study proposes giving students the opportunity to design mobile apps for their science learning. Students can prepare the software applications in the computer lab, defining the goal of the App, i.e., the data they need to collect and how to be collected for later applications. Once the application design is completed, it can be saved and later executed on a smartphone. Students are empowered with the capability to design and interact with the physical world through their own insight and programming determination. Xie et al. (2015) argued that the convergence of computing, connectivity, and content enables people to leverage their smartphones to solve problems they encounter in their daily life. For the students without much experience in computing programming or capabilities in operating sophisticated technology tools which are unaffordable for most high schools, the proposed graphic-based programming tools provide support and motivation for students participating in engineering design processes. For the specific case of App Inventor, it empowers all students to transition from being consumers of mobile learning applications to becoming creators through STEM engineering design processes.

Some suggestions about what students need to do and how teachers should help during the process of engineering design are adopted from Hynes et al. (2011). The further elaboration of the suggestions is given below. The suggestions should not be read as a rigid set of guidelines that must be followed, but rather as a set of guiding principles to consider in the teaching and learning of engineering. The engineering design process is a cyclical, stepwise process for solving real-world engineering problems. Oftentimes the task requires some jumping around from step to step.

Identify and define problems

When students are capable of identifying a need or problem in a given situation, they should be provided with the opportunity to do so. The problems should be ill-defined, and students need to acknowledge the design goals and identify the necessary constraints imposed on the problem. In addition, students might be given the opportunity to decompose a given situation in order to frame a problem in their own words (Koehler et al., 2005, Lemons et al., 2010). The problem needs to be open-ended with many possible solutions. This approach not only increases the likelihood of the students taking ownership of the problem, but it also provides students with an opportunity to practice critical thinking skills (Hynes et al., 2011). As the problem is ill-defined, students need to conduct some background research, and understand that there are many science and mathematics issues to consider when solving a real-world issue. Learning may begin with an exploration of students' interpretations and understandings of the science concepts to be addressed (Apedoe et al., 2008; Taber, 2003). Students will recognize that they need to fully explore the problem in order to be well-informed as to how to solve it. At this moment, teacher may scaffold the related curriculum which is necessary to the students. This approach allows students to comprehend that research is integral to the process of engineering design (Ennis & Greszly, 1991). As students research the need or problem and discover new ideas or constraints, they will redefine and clarify the problem.

Develop and select possible solution(s)

The ultimate purpose of engineering design is to create a solution or an end product that solves the problem. Students need to be able to justify and rationalize the solution which they pursue. This requires that a better possible solution be selected for the project. What may seem the best for one person may not always seem best for another person. Recording possible solutions for the design task takes into consideration the need for planning and teamwork. Students should actively collaborate in groups to foster individual learning and creativity. Through this process, students practice their communication skills with others and understand tradeoffs while forming ideas within the problem criteria and constraints (Mullins, Atman, & Shuman, 1999; Radcliffe & Lee, 1989).

Students are advised that a perfect solution is rarely available to real-world problem. This requires students to back-up their ideas with proper evidences and issues that are discovered through research (Dym et al., 2005). This also assures that students use their knowledge of mathematics and science in their own words to make informed decisions, constantly assessing each choice along the way.

Construct a prototype

Building things is often the concept students have about engineering design prior to exposure to any engineering design (Hynes et al., 2011). This is clearly not the case, as the previous two activities describe the need for sufficient planning before engineering construction can begin. Iterative prototyping until an final product is reached is a key component of this stage (Hynes et al., 2011; Koehler et al., 2005). As students iterate on their solution, it is important to allow them to fail and learn from those failures. Regarding the construction

ISSN:2149-8504 (online)

a physical model, some students may have the conception of using 3D printer to make their final product, or solution to a problem. A 3D printer should be treated as prototype maker, not only an end-product maker. In addition, a prototype is a representation or model of the final solution, which can be physical, virtual, or mathematical (Hynes et al., 2011).

There may be a number of prototypes developed throughout the engineering design process that build upon each other or represent different characteristics of the final solution (Hynes et al., 2011). The prototype may not always perform like the intended final solution. Instead, it should illustrate some fundamental functionality or look of the proposed final solution.

Test and evaluate the solution(s)

Students must develop their own experimental tests based on the constraints and requirements of the problem to judge and evaluate their solutions and prototypes (Trevisan et al., 1998). Regarding the proposed graphic-based programming tools, students may tinker with quick feedback and interactive computational practices such as testing and debugging, which are cognitively less demanding. This allows students to acquire computational problem-solving practices more easily. Ultimately, these tools become "technology-as-partner in the learning process" (Jonassen, Howland, Marra, & Crismond, 2008, p. 7) and can help students to extend these computational practices towards enhancing their general problem-solving skills.

The proposed graphic-programming tools can engage students in the building of digital products, thereby enabling programming activities to be used as a means to express their ideas. This can shape students' computational perspective about the computational tools and technological world. That is, computational perspectives entail students developing understandings of themselves and their relationships with others and the technological world (Lye & Koh, 2014). It is cautioned that the programming experience may be non-educative as students are merely doing it in the trial-and-error mode without actively reflecting on their experience (Lye & Koh, 2014). Hence, the students ought to be thinking-doing and not just doing (Lye & Koh, 2014).

In this stage of engineering design, students are not expected to get the final solution in the first trial, and debugging is one of the required skills to find the solutions. Debugging encompasses four steps: 1) recognize that something is not meeting the goal, 2) either decide to continue to pursue the original plan or come up with an alternative, 3) generate a hypothesis as to the cause of the problem, and 4) attempt to solve the problem (Bers et al., 2014). In the engineering design process, the steps of evaluating and improving, which require debugging, are particularly important in establishing a learning environment where failure rather than immediate success is expected and seen as necessary for the design process (Bers et al., 2014). Debugging skills are not limited to the arena of computer science. With appropriate support and explicit instruction, students can transfer debugging skills to activities outside of the programming context (Bers et al., 2014; Klahr & Carver, 1988).

As students have their final solution, they should present the design by detailing the specifications of their design and how it works scientifically (Apedoe et al., 2008). In this way, the presentation allows students to refine and connect their science and engineering knowledge. Meanwhile, to support the success of the above engineering design process and related learning activities, students should have the so-called Engineering habits of mind (Katehi, Pearson, & Feder, 2009; Basham & Marino, 2013). That is, in addition to acquiring knowledge and skills of engineering design, STEM education should also focus on the adoption of engineering habits of mind (Katehi, Pearson, & Feder, 2009; Basham & Marino, 2013), which include (1) systems thinking, (2) optimism and creativity, (3) collaboration and communication, and (4) attention to ethical considerations. Systems thinking requires students to recognize essential knowledge interconnections among the subject domains in STEM and their contributions to the value of engineering. Meanwhile, engineering systems may have effects that cannot be expected from the behavior of individual subsystems (Basham & Marino, 2013). In every unexpected challenge engineering possibilities and opportunities can be found. Optimism and creativity thus are inherent in the engineering design process. Engineering is also about team work which requires engineers' collaboration; collaboration leverages the perspectives, knowledge, and skills of team members to tackle a de-

ISSN:2149-8504 (online)

sign challenge (Basham & Marino, 2013). During team work, communication is essential to enable understanding of the requirements of an engineering problem, and to explain and justify the prototypes during the design process. Ethical considerations draw attention to the effects of engineering on society, including people and the environment.

The proposed learning task of engineering design

In science learning (for example Chemistry), complexity comes from its understanding of matter at three levels of representation: macroscopic, microscopic and symbolic (Gabel, 1999). Macroscopic refers to the observational experience in the laboratory and everyday life; microscopic level means the representation of the inferred nature of chemical entities (as atoms, ions, or molecules) and the relationships between them; symbolic level is the representation of the identities of entities (atoms, ions, or molecules) (Gilbert, 2005). It is difficult to develop an intuitive understanding of the connection between these three levels (Harrison & Treagust, 2002). However, integrating the three levels of representation would provide a greater conceptual understanding of the subject content (Gabel, 1999). Incorporating hands-on practical work into the chemistry classroom is one way to help students strengthen their understanding of the connections between the macroscopic and the microscopic (Gabel, 1999). Therefore, the proposed learning task is intended to create a learning environment supporting students to integrate multiple types of representations with hands-on work.

The purpose of learning engineering design in STEM is to encourage students to experience engineering with hands-on activities as a practical application of math and science knowledge. The required hand-on activities and exercises of knowledge and skills are aligned with the Kolb's (1984) experiential learning cycle (Fig. 1). During the process of using computational tools for the creation or tinkering, as suggested in this study, students access and exercise their knowledge through practical work.

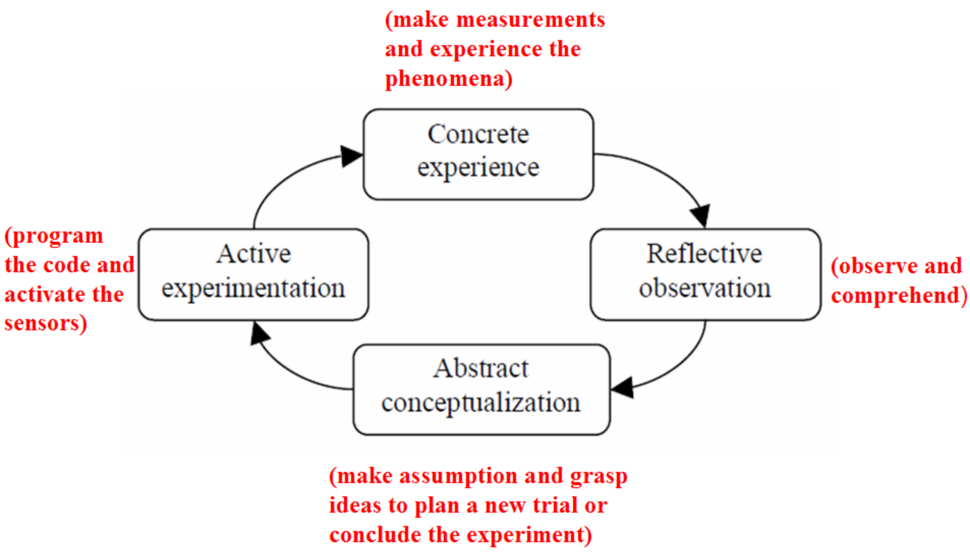


Figure 1. Modified Kolb's (1984) experiential learning cycle

The experiential learning cycle is proposed to guide the development of micro-activities (creation or tinkering with computational artifacts) that integrate these phases and allow for a fluent transition among different types of learning activities in the engineering design process. Kolb argued that learning from experience is an appropriate way to acquire knowledge: "Learning is the process whereby knowledge is created through the transformation of experience" (Conradi et al., 2011; Kolb et al., 2000). His experiential learning cycle illustrates how learners construct and refine their knowledge through experimentation. After having a concrete experience, one can reflect on observations, conceptualize abstractly how it might work, and test these newly formed concepts through active experimentation. If the resulting experience and reflection do not fit the con-

ISSN:2149-8504 (online)

ceptualizations, they are adapted and tested with new experimentations (Conradi et al., 2011). The proposed task of engineering design is to tackle one general concern about hands-on activities, in which students do not learn the underlying science concepts through these activities, or the knowledge to be learned can be delivered through direct instruction (Apedoe et al., 2008; Kirschner et al. 2006).

In this study, the proposed use of graph-programming tools for STEM learning can support a quick tinkering process, when aligned with Kolb's experiential learning cycle, in which students program the code and activate the sensors (active experiment), make measurements and experience the phenomena (concrete experience), observe and comprehend (reflective observation), and make assumptions and grasp ideas to plan a new trial or conclude the experiment (abstract conceptualization)(Fig. 2). The digital test environment provides a tangible experience of physical theories and phenomena and supports reflection and conceptualization of digital information in situ. Students actively participate as programming engineers in engineering design processes. Students access and exercise knowledge and skills in the subject domains of science, mathematics, and technology to support their meaningful engineering design. Engineering design provides students with possibilities to use various science and math materials that they have been taught throughout their education. By incorporating engineering into the frameworks of traditional math and science, the paradigm shifts from rigid, content driven, and discipline-specific subject content to a more problem-based engineering design process. (Hynes et al., 2011; Koehler et al., 2005).

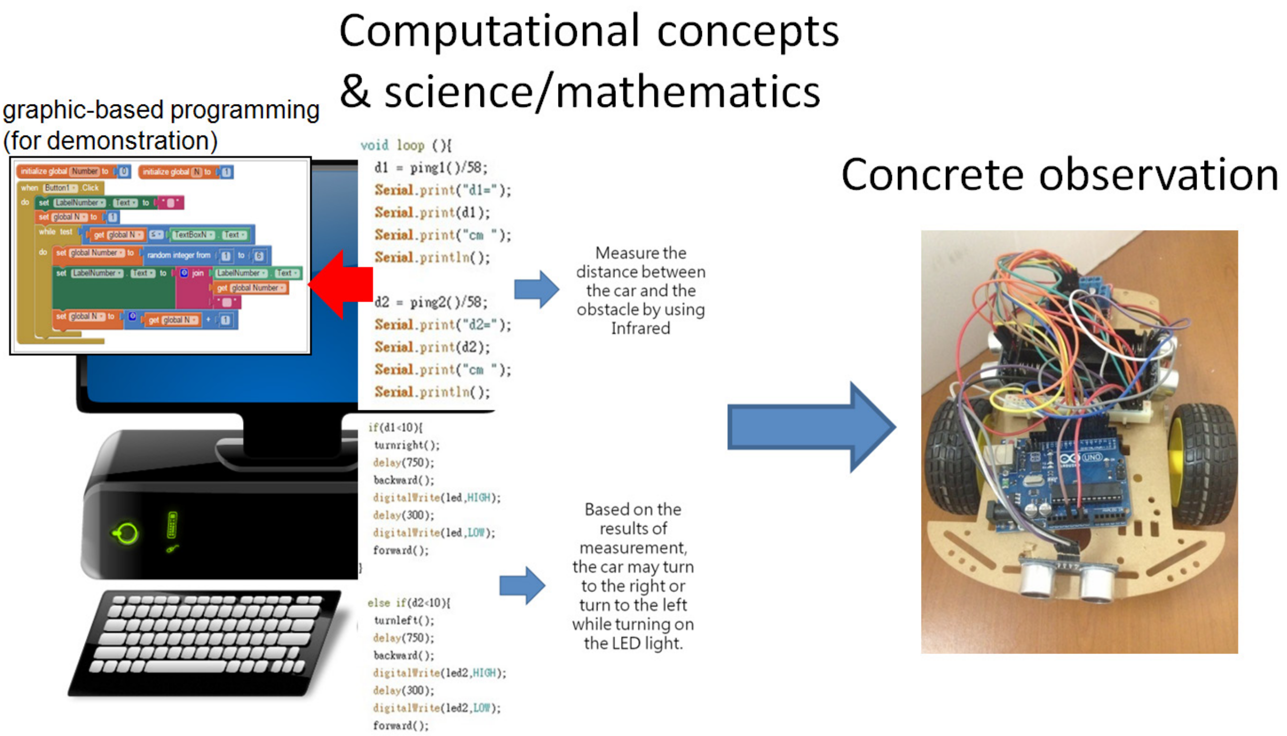


Figure 2. The proposed use of graph-programming tools for STEM learning

The proposed learning design and tools will help students acquire basic technicalities of programming which include computational concepts such as variables and loops. This study proposes that, in addition to the learning of computational concepts, students need to construct computational programs to access and manipulate the scientific data, and to implement the applications they design. Students learn to solve problems and acquire cognitive skills such as causal reasoning and metacognition. These are so-called computational practices, through which students can examine problem solving processes during programming. The proposed learning context may also entail students developing understandings of themselves and their relationships with the technology tools, smartphones, and the scientific world of physics, and hopefully transferring these competencies for general problem-solving. These are computational perspectives. The concepts, practices, and perspectives

ISSN:2149-8504 (online)

are three dimensions of computational thinking required for students (Lye & Koh, 2014; Wing, 2008).

Conclusions

There is little consensus about what STEM is, and how it can be taught in schools. This study is intended to provide a snap shot of prominent contemporary research and propose some design concepts aiming to contribute to better understanding of STEM and the potential of its use in education. In this study, STEM is designed to help students acquire real-world problem-solving skills by engaging them in an engineering design process. The purpose of learning engineering design is to encourage students to experience engineering with hands-on activities as a practical application of math and science knowledge. The proposed instructional design including hand-on activities and exercises of knowledge and skills has been aligned with Kolb's (1984) experiential learning cycle. Moreover, the technology tools of graphic-based programming are used for STEM because graphical-based programming tools have the characteristics of low floor, high ceiling, and wide walls (Lye & Koh, 2014; Papert, 1980; Resnick et al., 2009). Further proposed instruction design is the use of mobile app authoring tools, with which students can design the mobile apps in the computer lab, save the programs and later execute them on smartphones. Students are asserted to be empowered with the capability to design and interact with the physical world through their own insights and programming determinations. The convergence of computing, connectivity, and content enables students to leverage their smartphones to solve problems they encounter in their daily life (Xie et al., 2015). As the discussions of promising learning potential of the proposed designs await justifications, this study sheds new light on STEM and points to new possibilities for researchers and educators to adopt or tailor their own learning designs for the current digital-native generation.

References

Apedoe, X. S., Reynolds, B., Ellefson, M. R., & Schunn, C. D. (2008). Bringing engineering design into high school science classrooms: The heating/cooling unit. Journal of Science Education and Technology, 17(5), 454-465.

Barlex, D. (2007). STEM: an important acronym. D&T News (36). Warwickshire, UK: The Design and Technology Association.

Basham, J. D., & Marino, M. T. (2013). Understanding STEM education and supporting students through universal design for learning. Teaching Exceptional Children, 45(4), 8-15.

Bers, M. U., Flannery, L., Kazakoff, E. R., & Sullivan, A. (2014). Computational thinking and tinkering: Exploration of an early childhood robotics curriculum. Computers & Education, 72, 145-157.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. Educational psychologist, 26(3-4), 369-398.

Bucciarelli, L.L. (1994). Designing engineers. Cambridge, MA: MIT Press.

Carlson, L. E., & Sullivan, J. F. (2004). Exploiting design to inspire interest in engineering across the K-16 engineering curriculum. International Journal of Engineering Education, 20(3), 372-378.

Conradi, B., Lerch, V., Hommer, M., Kowalski, R., Vletsou, I., & Hussmann, H. (2011). Flow of electrons: an augmented workspace for learning physical computing experientially. In Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (pp. 182-191). ACM.

Douglas, J., Iversen, E., & Kalyandurg, C. (2004). Engineering in the K-12 classroom: An analysis of current practices and guidelines for the future. ASEE Engineering K12 Center. Retrieved from http://teachers.egfi-k12.org/wp-content/uploads/2010/01/Engineering_in_the_K-12_Classroom.pdf

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D. & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. Journal of Engineering Education, 94(1), 104-120.

Ennis, C. W., & Gyeszly, S. W. (1991). Protocol analysis of the engineering systems design approach. Research

ISSN:2149-8504 (online)

in Engineering Design, 3(1), 15-22.

Fortus, D., Dershimer, C., Krajcik, J., Marx, R., & Mamlok-Naaman, R. (2004). Design-based science and student learning. Journal of Research in Science Teaching, 41(10), 1081-1110.

Gabel, D. (1999). Improving teaching and learning through chemical education research: a look to the future. Journal of Chemical Education, 76, 548-554.

Gilbert, J. K. (2005). Visualization: A metacognitive skill in science and science education. In Visualization in science education (pp. 9-27). Springer Netherlands.

Glancy, A. W., Moore, T. J., Guzey, S. S., Mathis, C. A., Tank, K. M., Siverling, E. A., (2014). Examination of integrated STEM curricula as a means toward quality K-12 engineering education (Research to Practice). age, 24, 1.

González, M. Á., González, M. Á., Llamas, C., Martín, M. E., Vegas, J., Martínez, Ó., ... & Herguedas, M. (2014). Mobile phones for teaching physics: using applications and sensors. In Proceedings of the Second International Conference on Technological Ecosystems for Enhancing Multiculturality (pp. 349-355). ACM.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In Chemical education: Towards research-based practice (pp. 189-212). Springer Netherlands.

Hirsch, L. S., Kimmel, H., Rockland, R., & Bloom, J. (2005). Implementing pre-engineering curricula in high school science and mathematics. In Proceedings of the 35th Annual Conference Frontiers in Education, ed. H. Kimmel. Indianapolis, IN.

Hynes, M., Portsmore, M., Dare, E., Milto, E., Rogers, C., Hammer, D., & Carberry, A. (2011). Infusing engineering design into high school STEM courses. National Center for Engineering and Technology Education.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. Journal of computer assisted learning, 7(2), 75-83.

Jonassen, D., Howland, J., Marra, R.M., & Crismond, D. (2008). Meaningful learning with technology (3rd ed.): Pearson/Merrill Prentice Hall.

Katehi L., Pearson, G., & Feder, M. (Eds.) (2009). Engineering in K-12 education: Understanding the status and improving the prospects. Report from the Committee on K-12 Education for the National Academies. Washington DC: The National Academies Press.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. Educational psychologist, 41(2), 75-86.

Klahr, D., & Carver, S. (1988). Cognitive objectives in a LOGO debugging curriculum: instruction, learning, and transfer. Cognitive Psychology, 20, 362–404.

Koehler, C., Faraclas, E., Sanchez, S., Latif, S. K., & Kazerounian, K. (2005). Engineering frameworks for a high school setting: Guidelines for technical literacy for high school students. age, 10, 1.

Kolb, D. (1984). Experiential learning: Experience as the source of learning and development. Prentice-Hall.

Kolb., D., Boyatzis, R.E., & Mainemelis, C. (2000). Experiential learning theory: Previous research and new directions. Perspectives on cognitive, learning, and thinking styles. Lawrence Erlbaum, 227-247.

Kuhn, J., & Vogt, P. (2013). Smartphones as experimental tools: Different methods to determine the gravitational acceleration in classroom physics by using everyday devices. European J of Physics Education, 4(1).

Lemons, G., Carberry, A., Swan, C., Rogers, C., & Jarvin, L. (2010). The importance of problem interpretation for engineering students. In American Society for Engineering Education. American Society for Engineering Education.

Lye, S. Y., & Koh, J. H. L. (2014). Review on teaching and learning of computational thinking through programming: What is next for K-12?. Computers in Human Behavior, 41, 51-61.

Mann, E. L., Mann, R. L., Strutz, M. L., Duncan, D., & Yoon, S. Y. (2011). Integrating engineering into K-6 curriculum developing talent in the STEM disciplines. Journal of Advanced Academics, 22(4), 639-658.

Monteiro, M., Cabeza, C., & Martí, A. C. (2014). Exploring phase space using smartphone acceleration and rotation sensors simultaneously. European Journal of Physics, 35(4), 045013.

Moore, T. J., Tank, K. M., Glancy, A. W., Siverling, E. A., & Mathis, C. A. (2014a). Engineering to enhance STEM integration efforts, American Society for Engineering Education Annual Conference.

Moore, T. J., Stohlmann, M. S., Wang, H.-H., Tank, K. M., Glancy, A.W., & Roehrig, G. H. (2014b). Implementation and integration of engineering in K-12 STEM education. In J. Strobel, S. Purzer, & M. Cardella (Eds.), Engineering in precollege settings: Research into practice. Rotterdam, the Netherlands: Sense Publishers.

Moore, T. J., Mathis, C. A., Guzey, S. S., Glancy, A. W., & Siverling, E. A. (2014c). STEM integration in the middle grades: A case study of teacher implementation. In Frontiers in Education Conference (FIE), 2014 IEEE(pp. 1-8). IEEE.

Morelli, R., Uche, C., Lake, P., & Baldwin, L. (2015). Analyzing Year One of a CS Principles PD Project. In Proceedings of the 46th ACM Technical Symposium on Computer Science Education (pp. 368-373). ACM.

Mullins, C. A., Atman, C. J., & Shuman, L. J. (1999). Freshman engineers' performance when solving design problems. IEEE Transactions on Education, 42(4), 281-287.

National Research Council (1996). National science education standards. Washington, DC: National Academy Press.

Papert, S. (1980). Mindstorms: Children, Computers, and Powerful Ideas. Basic Books, New York.

Pendrill, A.-M., & Rohlen, J. (2011). Acceleration and rotation in a pendulum ride, measured using an iPhone 4. Physics Education, 46, 676-681.

Pitt, J. (2009). Blurring the Boundaries – STEM Education and Education for Sustainable Development. Design and Technology Education: An International Journal, 14(1), 37-48.

Radcliffe, D. F., & Lee, T. Y. (1989). Design methods used by undergraduate engineering students. Design Studies, 10(4), 199-209.

Resnick, M., Maloney, J., Monroy-Hernández, A., Rusk, N., Eastmond, E., Brennan, K., … Kafai, Y. (2009). Scratch: Programming for all. Communications of the ACM, 52, 60–67.

Roberts, P. (1995). The place of design in technology education. In D. Layton (Ed.), Innovations in science and technology education (pp. 27–38). UNESCO.

Trevisan, M. S., Davis, D. C., Crain, R. W., Clakins, D. E., & Gentili, K. L. (1998). Developing and assessing statewide competencies for engineering design. Journal of Engineering Education, 87(2), 185-193.

Vieyra, R. E., & Vieyra, C. (2014). Analyzing forces on amusement park rides with mobile devices. The Physics Teacher, 52(3), 149-151.

Vogt, P., & Kuhn, J. (2012). Analyzing free fall with a smartphone acceleration sensor. The Physics Teacher, 50(3), 182-183.

Wicklein, R. C. (2006). Five good reasons for engineering as the focus for technology education. The Technology Teacher, 65(7), 25.

Williams, J. (2011). STEM education: Proceed with caution. Design and Technology Education: An International Journal, 16(1).

Wing, J. M. (2008). Computational thinking and thinking about computing. Philosophical Transactions of the

ISSN:2149-8504 (online)

Royal Society of London A: Mathematical, Physical and Engineering Sciences, 366(1881), 3717-3725.

Xie, B., Shabir, I., & Abelson, H. (2015). Measuring the Usability and Capability of App Inventor to Create Mobile Applications. MIT Open access article, http://dspace.mit.edu/handle/1721.1/98913

ISSN:2149-8504 (online)

J-STEM

Journal of Research in STEM Education

j-stem.net