Facilitating educationally disadvantaged students' learning of torque using a design-based activity

Luecha Ladachart, Sirinapa Khamlarsai and Wilawan Phothong

University of Phayao, Thailand

Attention is increasingly being paid to integrated science, technology, engineering, and mathematics (STEM) education as a way to increase the workforce for STEM-related careers as well as to promote STEM literacy among citizens. This means that all students, including those who are educationally disadvantaged, are expected to not only acquire STEM knowledge but also to apply it to relevant situations in the future. Among the various approaches to STEM education, the design-based approach is promising. Although a significant amount of research has investigated students' STEM learning as a result of the design-based approach, little research has addressed the transfer of such learning, especially in the case of socioeconomically disadvantaged students. This mixed-methods research with an embedded design examines whether 18 ninth-grade students, who are from low-income families and attend an underfunded school, developed an understanding of torque and examines their ability to apply such understanding to new situations. Data were collected using a multiple-choice test comprising both conceptual and application questions (i.e., quantitative data) with prompts for students to write the reasons for their answers (i.e., qualitative data). Based on Wilcoxon signed-rank tests, a non-parametric statistical method, the quantitative results indicate that the students' scientific understanding significantly improved, but they struggled to apply that understanding to new situations. These quantitative results are augmented by an information-rich student and discussed based on a theory of learning transfer. Recommendations are proposed for improving the design-based activity to ensure STEM education is inclusive.

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Correspondence:
ladachart@gmail.com

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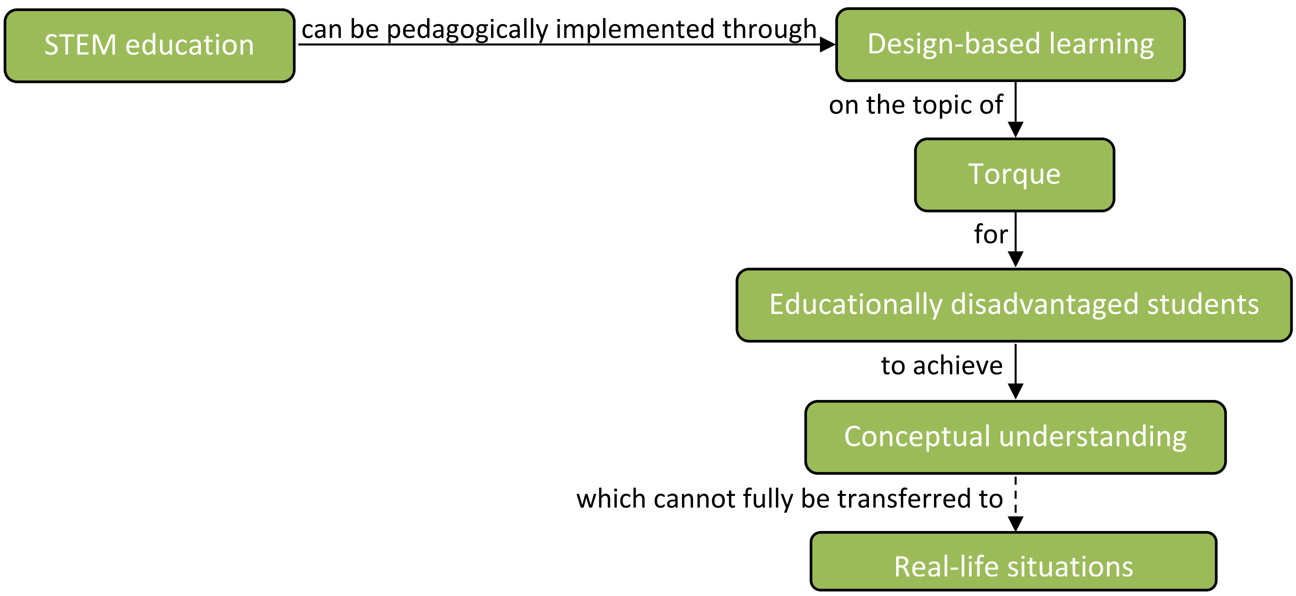

1 Introduction

As is the case in many countries (Li et al., 2020), Thailand's education system has recognized science, technology, engineering, and mathematics (STEM) education as a reform movement with the aims of promoting STEM literacy among citizens (Promboon et al., 2018). Falloon et al. (2020) have defined STEM literacy as "the knowledge, dispositions, capabilities and skills, deemed important for students' productive engagement with STEM-related study, careers, issues and practices" (p. 374). To achieve STEM literacy for all students, an engineering design process—the iterative process by which engineers design, evaluate, and improve solutions (e.g., artifacts, devices, and systems) to real-world and human-centered problems under certain constraints and criteria specified by users or consumers of those solutions (Dym et al., 2005)—is pedagogically proposed as a promising approach to teaching and learning STEM in K–12 or basic education (Arik & Topcu, 2020). In this regard, engineering is considered not only as the discipline most relevant to students' everyday experiences but also the discipline that connects science, technology, and mathematics together (Kelly & Knowles, 2016), thereby reflecting the integrated nature of STEM education (Quinn et al., 2020).

Various models of a design-based approach have been proposed in science education, such as design-based science (Fortus et al., 2004), design-based learning (Ellefson et al., 2008), and learning by design (Kolodner et al., 2003). These models are based on the premise that students can meaningfully learn STEM through a pedagogical process that is similar to the process engineers use to create products to solve engineering problems (i.e., the engineering design process). However, the results of examining the influence of the design-based approach on students' acquisition of scientific understanding have been mixed. Whereas most research indicates that the design-based approach can facilitate students' learning of science (Fortus et al., 2004; Kolodner et al., 2003; Mehalik et al., 2008), it is also evident that students can still hold misconceptions after design-based learning (Damkenbring & Capobianco, 2016; Marulcu & Barnett, 2013). As a result, researchers recommend integrating additional strategies, such as demonstrations targeting students' misconceptions (Schnittka & Bell, 2011) and communicative scaffolding (Chusinkunawut et al., 2021), into design-based learning to enhance its effectiveness in terms of developing students' scientific understanding.

As increasing the workforce for STEM-related careers is another goal of STEM education (White & Delaney, 2021), students should not be expected to only have disciplinary knowledge of STEM (Godwin & Potwin, 2017). Rather, students should also have an ability to apply such knowledge to new situations—an ability that, Gallagher (2000) argues, is a central part of learning. As knowledge in use (i.e., applicable knowledge) requires not only conceptual knowledge but also situational, procedural, and strategic knowledge, it is higher quality and more sophisticated than conceptual knowledge (de Jong & Ferguson-Hessler, 1996). While conceptual knowledge is often recognized as a prerequisite for applicable knowledge (Apedoe et al., 2012; Yu et al., 2015), according to Bloom's (1965) taxonomy of educational objectives in the cognitive domain, this is not always the case. In statistics learning, for example, Novak (2014) found that students developed applicable knowledge but not conceptual knowledge. Additionally, Wang and Andre (1991) found that integrating questions about the application of scientific knowledge into texts can enhance students' conceptual understanding. Thus, acquiring one type of knowledge does not guarantee the acquisition of the other type of knowledge.

Since conceptual knowledge and applicable knowledge are distinct yet related, several studies have investigated whether students acquire scientific knowledge and whether they can apply such knowledge to new situations as a result of design-based learning. Some studies have indicated that, because it focuses on real-life applications, the design-based approach can facilitate students' acquisition and application of scientific knowledge (Fortus et al., 2004; Wendell & Lee, 2010). However, other studies have demonstrated that, while students' performance might improve in design, where they can apply scientific knowledge (Dixon & Brown, 2012), they "still struggled to accurately transfer science concepts" (Kelly & Sung, 2017, p. 96). Despite these mixed results, mostly gained from typical students, some studies have also shown that the design-based approach has particular potential to facilitate science learning for socioeconomically disadvantaged students from low-income families (Kolodner et al., 2003; Mehalik et al., 2008; Silk et al., 2009). Thus, in addition to investigating whether the design-based approach can improve socioeconomically disadvantaged students' scientific understanding, it is crucial to examine whether they can transfer such understanding to new situations.

According to Kellaghan (2001), a student can be regarded as educationally disadvantaged if "the competencies and dispositions which he/she brings to school differ from the competencies and dispositions which are valued in schools" (p. 5) due to economic, social, and cultural factors such as poverty, the use of a second language in schools, and whether the student has an indigenous background. Based on this definition, students from low-income families can be viewed as educationally disadvantaged. As research has shown that students' socioeconomic status is an important factor that can influence their achievement in STEM learning (Broer et al., 2019), students whose socioeconomic status differs can benefit differently from a particular kind of instruction. Among students with a low socioeconomic status, Han et al. (2015) found that low-achieving students benefited more than high- and moderate-achieving students from STEM education through project-based learning. Given the potential of design-based learning for students who are socioeconomically disadvantaged, this mixed-methods study aims to investigate whether design-based learning can improve this type of students' scientific understanding and whether they can apply such understanding to new situations—an issue that is not sufficiently addressed in the literature.

2 Design-based learning

The notion of using design-based activities to facilitate students' learning is not novel, particularly in science education. Lewis (2006) has distinguished two approaches to design-based learning in science education: (1) design through science and (2) science through design. In design through science, "how science becomes the vehicles for prompting design" (p. 269) is highlighted. Students collaboratively engage in inquiry-based instruction to construct scientific knowledge before they are challenged to use such knowledge in an engineering design process (Fortus et al., 2005). Fortus et al.'s (2004) model of design-based science is an example, as this model includes five stages, namely (1) identifying and defining contexts, (2) conducting background research, (3) developing personal and group ideas, (4) constructing 2D and 3D artifacts, and (5) testing to gain feedback. It is the second stage, that of conducting background research, in which students engage in activities (e.g., searching for relevant information, reading selected materials, observing the teacher's demonstration, and engaging in scientific inquiry) to gain scientific knowledge to be used in the third stage, in which students develop ideas about possible designs. Arguably, the design-based approach to STEM education in Thailand can also be considered as design through science given that the Institute for the Promotion of Teaching Science and Technology (2015) describes six steps in the instructional guidelines based on the engineering design process, namely (1) identifying the problem; (2) searching for related information; (3) designing a solution; (4) planning and development; (5) testing, evaluating, and improving the design; and (6) presentation.

In the science through design approach, the notion that "the [engineering] design process [...] is used as the vehicle for teaching science concepts" (Lewis, 2006, p. 268) is emphasized. Students are expected to collaboratively construct scientific knowledge during design-based activities (Apedoe et al., 2012). Apedoe et al.'s (2008) model of design-based learning is an example; this model consists of seven stages, namely (1) creating designs, (2) evaluating outcomes, (3) generating reasons, (4) testing ideas, (5) analyzing results, (6) generalizing results, and (7) connecting to big ideas. Unlike in design through science approaches, students are not expected to already have scientific knowledge to be applied in the engineering design process. Rather, they can initially use their prior knowledge, which could include misconceptions, in designing products. Their initial designs are subsequently empirically evaluated according to specific criteria and requirements. Thereafter, students are encouraged to provide reasons why their designs work or do not work. Such reasons can then lead to the formulation of hypotheses to be tested using scientific inquiry. Once the students collect and analyze data during scientific inquiry, the results thereof can be connected to scientific concepts. It is these scientific ideas that students can use to improve their initial designs. As illustrated in this example model, scientific inquiry is intentionally integrated into the engineering design process to ensure that students have an opportunity to construct scientific knowledge via engaging in a design-based activity.

Lewis (2006) has noted that "whether the approach is science through design or design through science, the effect is the same" (p. 269) in the sense that both approaches mimic complementarities between science and design in the real world. However, it can be argued that a "design-science gap" (Vattam & Kolodner, 2008) arises due to the differing natures of engineering and science, which can potentially prevent students from acquiring scientific knowledge during design-based activities. Schauble et al. (1991) have observed that, if students perceive a design challenge as an engineering problem, they tend to solve such a design challenge, even by trial and error, until they achieve success, without attempting to construct scientific knowledge. If students shift their perception of the design challenge to view it as a scientific problem, they are more likely to conduct scientific experiments and thus acquire scientific knowledge. The existence of the design-science gap may help explain the mixed results of using design-based approaches to facilitating students' scientific conceptions. Moreover, given that students' prior knowledge is often resistant to change even when explicitly challenged (Chinn & Malhotra, 2002), it is likely that such prior knowledge will remain after students engage in design-based learning (Damkenbring & Capobianco, 2016; Marulcu & Barnett, 2013). Thus, more research on the influence of design-based learning on students' scientific knowledge is needed, especially in the case of socioeconomically disadvantaged students.

3 Transfer of learning

It seems more challenging for students to transfer their acquired knowledge to novel yet related situations than to acquire scientific knowledge in a design-based activity (Apedoe et al., 2012; Dixon & Brown, 2012; Kelly & Sung, 2017). It can be argued that for learning transfer to occur, at least two conditions are required: First, students must construct a mental map, which can be defined as "the representation of a specific pattern of actions necessary to perform a task within the [learning] situation" (Gilbert et al., 2011, p. 828). For this condition to occur in the context of design-based learning, it is important that students are able to "notice" critical aspects of what they are designing to accomplish a given challenge (Chase et al., 2019). According to Lobato et al. (2012), to notice means to select, interpret, and work with critical aspects when multiple sources of information compete for students' attentions. While the ability to notice critical aspects is necessary, it is not sufficient given that the critical aspects may be ignored by students shortly after they are noticed. Therefore, it is also necessary that students focus on critical aspects for a period of time (Malkiewich & Chase, 2019) so that they can investigate those aspects in detail and construct a mental map that is consistent with scientific knowledge. It is recommended that contrasting design cases be strategically used to facilitate students' noticing and then focusing on critical aspects of the designs (Chase et al., 2019).

Once students construct a mental map regarding what makes designs work, the second condition is that they must identify connections between the learning and the applied situations, so that they can appropriately use such a mental map in the applied situation (Simons, 1999). Different kinds of learning transfer can occur based on this condition (Gilbert et al., 2011). According to Royer (1979), learning transfer can be categorized as "near transfer" and "far transfer," with the former referring to "a situation where the stimulus complex for the transfer event is very similar to the stimulus complex for the original learning event" (p. 55) and the latter referring to a "situation where the stimulus complex for the transfer event would be somewhat different from the stimulus complex for original learning" (p. 56). Following this description, Royer (1979) went on to note that near transfer can be used to refer to "the transfer from one school-learned event to another school-learned event" (p. 56) and that far transfer can be used to refer to "the situation where information learned in school transfers to a real-world (out of school) problem or learning situation" (p. 56). Given this categorization, however, it is important to note that, according to Simons (1999), "this is no dichotomy; rather, it is a dimension of distance" (p. 581). Regardless of the types of learning transfer, it is not possible that students can apply or transfer the knowledge they have constructed in the original situation to a new situation without both conditions being satisfied.

4 Research questions

A significant amount of research has examined the influence of design-based learning on students' scientific knowledge, with mostly positive results (e.g., Apedoe et al., 2008; Chusinkunawut et al., 2021; Fortus et al., 2004; Kolodner et al., 2003; Mehalik et al., 2008; Schnittka & Bell, 2011; Wendell & Lee, 2010). Despite this, little is known about whether learning is transferred from a design-based learning situation to new situations (Apedoe et al., 2012; Dixon & Brown, 2012; Kelly & Sung, 2017), especially in the case of educationally disadvantaged students from low-income families and from underfunded schools. According to the Organisation for Economic Co-operation and Development (2018), educationally disadvantaged students can be defined in terms of their economic, social, and cultural status when compared to that of all students in a country. Thus, the current study using mixed-methods research investigates whether a design-based activity, combined with the strategic use of contrasting cases, can improve socioeconomically disadvantaged students' scientific understanding and, if so, whether they can transfer such understanding to new situations. Accordingly, the following two research questions were formulated:

1. Can a design-based activity in combination with the strategic use of contrasting cases support socioeconomically disadvantaged students to improve their scientific understanding?
2. If yes, can the design-based activity in combination with the strategic use of contrasting cases support the socioeconomically disadvantaged students to transfer their scientific understanding to new situations?

5 Research methods

The current study utilizes a mixed-methods research approach to examine whether design-based learning combined with a contrasting-cases strategy can facilitate socioeconomically disadvantaged students' conceptual understanding of a scientific concept and, if so, whether they can apply such understanding to new situations. Johnson et al. (2007) define mixed-methods research as "the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration" (p. 123). A key premise of mixed-methods research is that it can offer "a better understanding of research problems than either (qualitative or quantitative) approach alone" (Creswell & Plano Clark, 2011, p.5). Given that that mixed-methods research methods vary depending on how qualitative and quantitative approaches are combined and which one is dominant over the other, this study uses quantitative-dominant mixed-methods research (Johnson et al., 2007) using an embedded design (Creswell & Plano Clark, 2011), as qualitative data were collected from an information-rich student's written reasoning in the pretest and the posttest to augment the quantitative results gained from the comparison of scores between those tests.

5.1 Context of the study

The current study was conducted in a secondary school located in a rural district in Chiang Rai, which is the northernmost province of Thailand. The per capita income of people living in this province is about 2,175 USD per annum (Provincial Community Development Office of Chiang Rai, 2019), which is about 24% of the average of the country (National Statistical Office, 2019). Specifically, the district where the school is located has the highest number of families (158) whose per capita income is lower than the minimum figure of 1,136 USD per annum (Provincial Community Development Office of Chiang Rai, 2019)—this number of families is about 39% of all families (406) that have a per capita income lower than the minimum figure in the province. With a total of 100 students studying in the seventh to 12th grades, the school can be considered small sized (Wannagatesiri et al., 2014). The school has a total of 11 teachers, including three science teachers. Of these three science teachers, only one teacher has a bachelor's degree in teaching physics; thus, she is responsible for teaching content associated with physics at almost all grade levels. It was this teacher (i.e., the second author) who voluntarily participated in the current study, as she is interested in using design-based learning in a manner that is appropriate and practical for her school and students. Her interest concurs with that of Promboon et al. (2018), who have argued that STEM education in Thailand should not be one size fits all. Rather, STEM education should be implemented flexibly according to school contexts since schools' economic statuses are unequal in the country. As schools in Thailand typically receive their budget from the government based on the number of students they teach, this school has continuously faced financial limitations, which has resulted in shortages of apparatus, equipment, and materials. Ultimately, these shortages affect the quality of the education provided by the school, which in turn gradually reduces the number of students enrolled in the school, as parents with sufficient income decide to send their children to larger schools in the cities that can offer better quality education. As a result, many of the school's students are socioeconomically disadvantaged in comparison to most students in the country or even in the district. Based on the school's records since 2018, about 2% to 6% of students have dropped out of the school each year.

5.2 Participating students

The only ninth-grade class in the school, which consists of 21 students, participated in the current study, as they agreed to accept an invitation from their teacher (i.e., the second author) to voluntarily engage in the design-based activity. These students included 13 boys and eight girls. At the time when the current study began, they were 14–15 years old. Based on a survey conducted immediately prior to the implementation of the design-based activity, 19 students indicated that they had limited experience in terms of designing things, whereas the remaining two students revealed that they had never experienced it at all. Thus, the current study offered these students an early experience of the process of engaging in engineering design to collaboratively solve a real-life problem. However, three boys were absent on the day on which the post-measurement was conducted. Therefore, these three students were excluded from the current study. The data from 18 students (10 boys and eight girls) were used to address the research questions of the study. These students are considered socioeconomically disadvantaged due to the low incomes of their families, who are mainly engaged in agricultural or labor work. Moreover, based on classroom observations, some of them had difficulties with mathematical calculations such as multiplication and division.

5.3 Design-based activity

Of the various models of design-based approaches to teaching and learning science (e.g., Fortus et al., 2004; Kolodner et al., 2003), Apedoe et al.'s (2008) model of design-based learning was selected as the instructional framework that would be used to develop the design-based activity. This model describes the engineering design process as a seven-stage cycle in which students (1) create designs, (2) evaluate outcomes, (3) generate reasons, (4) test ideas, (5) analyze results, (6) generalize the results, and (7) connect their findings to big ideas. This model was chosen because it provides the students with an opportunity to use their prior knowledge and ideas to design initial products before testing and reasoning why some of those products may work better than others. This process can lead students to formulate hypotheses regarding the factors that might make some products work well, which can subsequently lead to scientific inquiries (e.g., exploration and experimentation). As opposed to the nationally proposed model of the Institute for the Promotion of Teaching Science and Technology (2015), in terms of which students are mainly expected to have a scientific understanding before they are to apply that understanding to solve an engineering problem, this model allows students to construct a scientific understanding during the engineering design process; thus, this model can be considered as a form of "science through design" according to Lewis's (2006) classification of design-based learning.

The design-based activity began by introducing the students to a problem via a video on YouTube and a post on the internet explaining that people can accidentally kick an ordinary table's legs when they walk close to it. While such an accident can be viewed carelessness on the part of the individuals who kick the table, it can also be regarded as problematic from the perspective of the table's designers (Norman, 2013). Thus, this problem was discussed to make the point that an ordinary table can be redesigned to better prevent such accidents, for example by moving its legs inward by a certain distance. It was then demonstrated to the students that such prevention can be achieved at the expense of the table's ability to support less weight at its corners. After discussing the pros and cons of various table designs, the students were divided into five groups to design a new kind of table with specific requirements in terms of height, width, length, and movability using a set of materials and equipment that included a piece of corrugated plastic, eight wooden sticks, a roll of self-fusing tape, a ruler, a cutter, 10 25-gram weights, a human model, and eight iron nuts. Key requirements were that the designed table must support a maximum weight at each of its corners and that the table's legs must not be prone to being kicked by the human model.

Following Apedoe et al.'s (2008) model of design-based learning, each group of students designed and prototyped a table using their prior knowledge and ideas, resulting in a variety of designed tables. One notable difference among the designed tables was how each group of students used the nuts. While it was clear what the other material and equipment would be used for (e.g., a piece of corrugated plastic for the table's top and wooden sticks for the table's legs), the purpose of the nuts was less clear; thus, there were various ways in which the nuts could be used. Given students' natural tendency towards functional fixation when engaging in design-based activities, each group of students attached the nuts to different components of their tables (e.g., the top end, the bottom end, or both ends of each leg). These differences resulted in variations in their tables' abilities to support weight when testing, which involved placing 25-gram weights, one by one, on each corner until the tables overturned. Based on the results of the testing process, the entire class compared and discussed the differences among their designed tables to determine why some could support more weight than others. Using the strategy of contrasting cases (Chase et al., 2019), some students were able to notice that, when they placed some nuts on the center of their table's top, the table could support considerably more weight. This point highlighted that the position of the nuts might be a critical factor, which should be investigated in future inquiries conducted by the students.

Figure 1. A lever made from a meter ruler hung on a test-tube stand.

In response to a guiding question as to whether and how the position of the weights placed on an object (e.g., a table) might result in it overturning or rotating, each group of students conducted a scientific inquiry to explore the factors that might cause a lever to balance horizontally or incline to a direction. Due to the limited apparatus and equipment available at the school, a meter ruler hung on a test-tube stand was adopted as a lever to allow each group of students to either vary the amount of mass or change the position of the mass between the two sides of the lever to observe whether it would balance or tilt (see Figure 1). After the students analyzed the outcomes of this scientific inquiry, the scientific concept of torque was introduced and discussed using a simulation from PhET Interactive Simulations (University of Colorado, 2020). Some applications of the scientific concept of torque were briefly presented, such as a nail clipper, a two-wheel trolley, a paper trimmer, and an ice tong. Thereafter, each group of students was challenged to redesign a new table, using the same set of materials and equipment, to achieve a better result based on the same requirements. This design-based activity lasted about four weeks, with the students spending about three hours per week on it. It was evident from the testing process that the students were able to redesign the tables to support more weight. However, as this could have been achieved by trial and error (Park et al., 2018), it was not clear whether the students also improved their scientific knowledge as a result of the design-based activity.

5.4 Data collection

To examine the influence of the design-based activity on the students' knowledge of torque and the degree to which that knowledge might be transferred to other real-life situations in addition to the original situation of designing a table, a test was developed to assess the students' knowledge before and after the design-based activity. In so doing, a number of questions from the literature (Holzer & Andruet, 2000; Marulcu & Barnett, 2013; McGinn & Roth, 1998; McKenna & Agogino, 1998; Rimoldini & Singh, 2005) were selected and reviewed. The selected questions were then translated and sent to three physics educators who are fluent in both Thai and English to assess the questions' validity and readability. This process resulted in 10 four-choice questions. As can be seen in Table 1, these questions can be divided into two kinds, namely conceptual and application questions, as this distinction is reflected in Bloom's (1965) taxonomy of educational objectives in the cognitive domain. There are six conceptual questions, which ask the students to compare the net torque of the lever on which different forces act and then select a lever that would balance and to determine the net force that would make a lever balance. The remaining four questions are application questions, which focus on predicting whether and how a seesaw would rotate when two children sit on it at opposite ends, selecting a screwdriver to open a paint can with the least effort, and calculating the minimum force required or determining the pivot point to lift an object using a lever.

Table 1. Descriptions of the items in the test.

Item	Type	Source	Difficulty
1. Given a picture of two boys of the same mass and sitting on each side of a seesaw at different distances from its pivot, students are asked to predict whether and how the seesaw would rotate.	Application question	Holzer and Andruet (2000)	0.31
2. Given three pictures, each of which shows two or three forces acting vertically on a horizontally oriented lever at different points, students are asked to compare and rank the net torque of the levers.	Conceptual question	Rimoldini and Singh (2005)	0.31
3. Given three screwdrivers of different lengths, students are asked to choose one with which to lever open the lid of a paint can.	Application question	Marulcu and Barnett (2013)	0.52
4. Given a situation in which a boy is moving into a new residence and must lift a 120-newton television onto a pickup truck using a 8-meter-long lever, students are asked to determine the minimum force necessary to achieve this when the pivot point is fixed.	Application question	McKenna and Agogino (1998)	0.38
5. Given the same situation described in the fourth item, students are asked to determine the position of the lever's pivot when provided with the maximum effort the boy exerts to lift a 150-newton refrigerator.	Application question	McKenna and Agogino (1998)	0.24
6. Given three pictures, each of which shows two to four forces acting vertically on a horizontally oriented lever at different points, students are asked to choose the lever that is in balance.	Conceptual question	Rimoldini and Singh (2005)	0.48

Item	Type	Source	Difficulty
7. Given three pictures, each of which shows two forces acting on the ends of a lever, students are asked to compare and rank the net torque of the levers. Note that these three pictures differ in terms of the levers' orientation and the forces' direction. Specifically, the first lever is horizontally oriented, and the forces act on it vertically. The second lever is not horizontally oriented, but the forces act on vertically. The third lever is not horizontally oriented, nor the forces act on it vertically.	Conceptual question	Rimoldini and Singh (2005)	0.66
8. A horizontally oriented lever of 14 units in length is hung in balance at its central point with the ceiling. If a 50-gram object is then hung at 6-unit point away from its hanging point at one side, students are asked to determine the net force required to act downward on the other side of the lever at 3-unit point far from its hanging point in order to keep the lever balanced.	Conceptual question	McGinn and Roth (1998)	0.41
9. A horizontally oriented lever of 10 units in length is hung by one of its ends from the ceiling. If a 30-gram object is then hung at 3-unit point away from its hanging point, students are asked to determine the net force required to act upward on the lever at 9-unit point away from its hanging point in order to balance the lever.	Conceptual question	McGinn and Roth (1998)	0.55
10. A horizontally oriented lever of 14 units in length is hung in balance at its central point with the ceiling. If a 90-gram object is then hung at 4-unit point away from its hanging point at one side, students are asked to determine an object's weight to be hanged at the other side of the lever at 6-unit point far from its hanging point in order to keep the lever balanced.	Conceptual question	McGinn and Roth (1998)	0.66

The test was completed by 29 students in the same grade from a slightly more privileged school before it was used in the current study. The result of this pilot test indicated that the test was rather difficult, as the average score obtained by these students was about 4.55 out of 10 (SD = 1.70). By calculating each question's difficulty, it was revealed, as can be seen in Table 1, that one question can be considered as "very difficult," as its difficulty value was 0.24; four questions can be considered as "difficult," as their difficulty values ranged from 0.31 to 0.41; three questions can be considered as "intermediate," as their difficulty values ranged from 0.48 to 0.55; and two questions can be considered as "easy," as their difficulty values were both 0.66, resulting in the overall difficulty value of the whole test being 0.46, which can be considered as "intermediate" (Verdugo et al., 2016, p. 41). Not surprisingly, the four application questions can be considered as either "very difficult" (one) or "difficult" (three), while the six conceptual questions can be considered as either "easy" (two), "intermediate" (two), or "difficult" (two). As was suggested by the teacher of these students, the result of this pilot test also led to minor revisions in the wording of some questions to increase their readability. Once revised, the test was administered to the participating students before and after the implementation of the design-based activity. The participating students completed the test within 30 to 45 minutes on both occasions.

5.4 Data analysis

The quantitative data from the students who completed both measurements were descriptively and inferentially analyzed using JASP (Goss-Sampson, 2020). For the descriptive analysis, the means of the students' scores for all questions, the conceptual questions only, and the application questions only in both measurements were calculated. Thereafter, an inferential analysis was conducted to compare their average scores before and after engaging in the design-based activity. In doing so, the normal distribution was first examined using the Shapiro-Wilk test (Field, 2009). This test indicated that the scores for pre-measurement were normally distributed (p = .158), yet the scores for post-measurement were not (p = .021). Thus, instead of using a paired-samples t-test, a Wilcoxon signed-rank test was utilized (Morgan et al., 2013) to compare the means of the collective scores. Subsequently, a similar method was employed to compare the means of the scores from only the conceptual questions and then the means of the scores from only the application questions to address the first and second research questions, respectively. In cases in which significant differences were detected, effect size was calculated using the matched rank biserial correlation (Kerby, 2014). Furthermore, Hake's (1998) learning gains for each student in terms of the collective score, the score for conceptual questions only, and the score for application questions only were also calculated as the ratio of the actual average gain (%<post> – %<pre>) to the maximum possible average gain (100 – %<pre>). The learning gains were descriptively interpreted using Hake's (1998) criteria that a value less than 0.0 indicates a regression, a value equal to 0.0 no progression, a value between 0.0 and 0.3 low progression, a value between 0.3 and 0.7 moderate progression, and a value greater than 0.7 high progression. Given that Hake's formula (1998) standardizes students' learning gains, a Wilcoxon signed-rank test was also used to determine whether the students' learning gains significantly differed between the two types of questions. In addition to these quantitative analyses, the students were asked to write the reasoning for their answers in spaces provided on the tests. Their written reasons were purposively sampled to serve as qualitative data using information-rich criteria (Patton, 2002) to better understand and illustrate the students' learning gains and difficulties.

6 Research results

6.1 Descriptive results

A descriptive analysis, as can be seen in Table 2, indicates that the students performed poorly in the test prior to the design-based activity. Their average score was 3.28 out of 10 (SD = 1.45). After the design-based activity, these students demonstrated an improvement, as their average score was 4.22 (SD = 1.26). For the conceptual questions, their initial average score is 1.78 out of 6 (SD = 1.22). After the design-based activity, their average score increased to 3.06 (SD = 0.87). Regarding the application questions, the students' initial average score was 1.50 out of 4 (SD = 0.92). After the design-based activity, their average score decreased to 1.17 (SD = 0.79).

Table 2. Descriptive results of the students' scores in the pre- and post-measurements.

Statistics	All the questions (10 items)		Only the conceptual questions (6 items)		Only the application questions (4 items)	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Mean	3.28	4.22	1.78	3.06	1.50	1.17
Standard deviation	1.45	1.26	1.22	0.87	0.92	0.79

6.2 Inferential results

While the improvement in the collective scores for all questions is small, the Wilcoxon signed-rank test indicates (see Table 3) that the students' average score in the post-measurement was significantly higher than that in the pre-measurement, $W = 21.50$, $p = .026$, with effect size of 0.59. This effect size can be interpreted as medium (Morgan et al., 2013). To better understand this improvement, an inferential analysis of the students' average scores for each type of question was also performed. For the conceptual questions, the Wilcoxon signed-rank test confirms that the students' average score in the post-measurement is significantly higher than that in the pre-measurement, $W = 10.000$, $p = .002$, with effect size of 0.83. This effect size can be interpreted as large (Morgan et al., 2013). For the application question, the Wilcoxon signed-rank test confirms that the decrease in the students' average score is not significant, $W = 49.500$, $p = .812$.

Table 3. Inferential results of the students' scores in the pre- and post-measurements.

Types of questions	W	p	df	Effect size
All the questions (10 items)	21.500	.026	17	0.59
Only the conceptual questions (6 items)	10.000	.002	17	0.83
Only the application questions (4 items)	49.500	.812	17	-

6.3 Learning gains

To illustrate the results, Hake's (1998) formula for the learning gain achieved by each student was calculated. As can be seen in Figure 2, for the whole test, 12 out of 18 students (66.67%) demonstrated some degree of progression. More specifically, two students demonstrated high progression, as their learning gains were greater than 0.7. Four students demonstrated moderate progression, with learning gains between 0.3 to 0.7. Six showed low progression (between 0.3 and 0.7). However, four students did not exhibit progression, and two students regressed.

However, when considering each type of questions separately, it appears that the learning gains resulted mainly from the scores on the conceptual questions. For the conceptual questions, 14 of 18 students (77.78%) demonstrated some degree of progression, as Figure 3 illustrates. More specifically, one student demonstrated high progression, seven student showed moderate progression, and six students exhibited low progression. However, three students did not demonstrate progression, and one student regressed to a significant extent. For the application questions, as Figure 4 shows, only three students demonstrate progression, six students did not exhibit progression, and nine students showed regression.

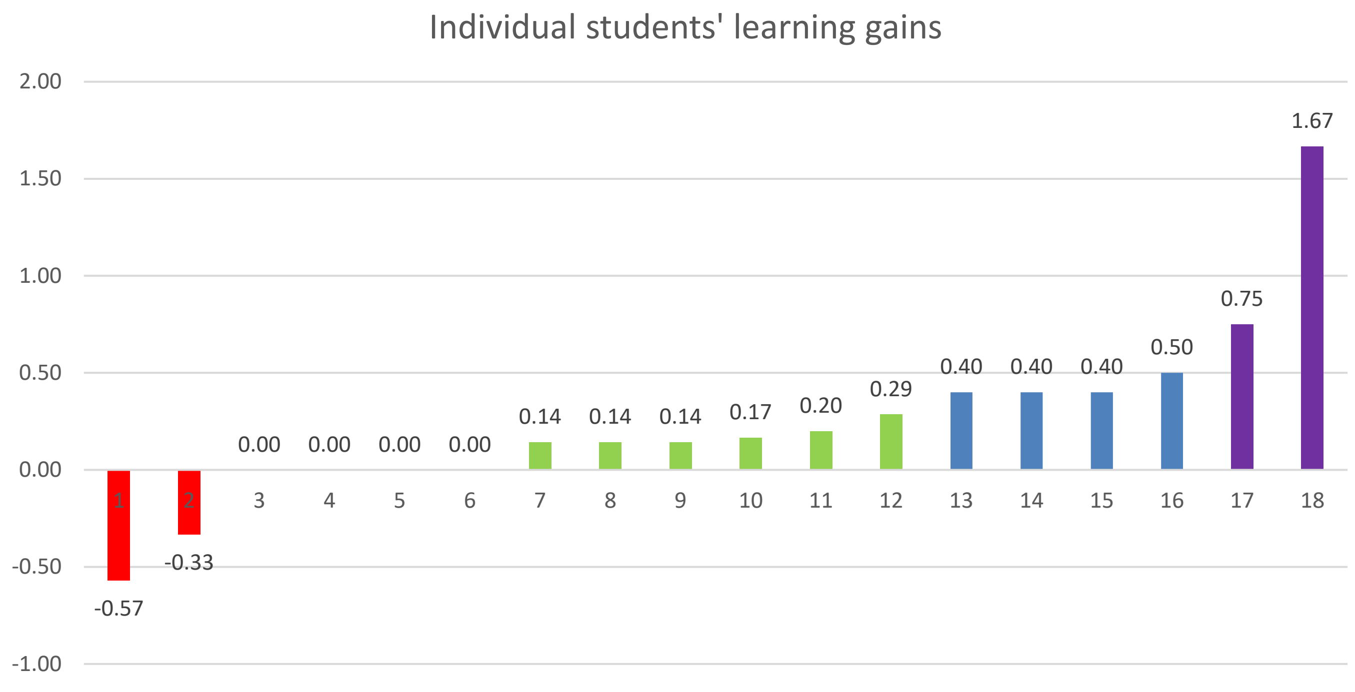

Figure 2. Distribution of the students' learning gains for all questions. Note that individual students are ordered according to their learning gain only in this respect.

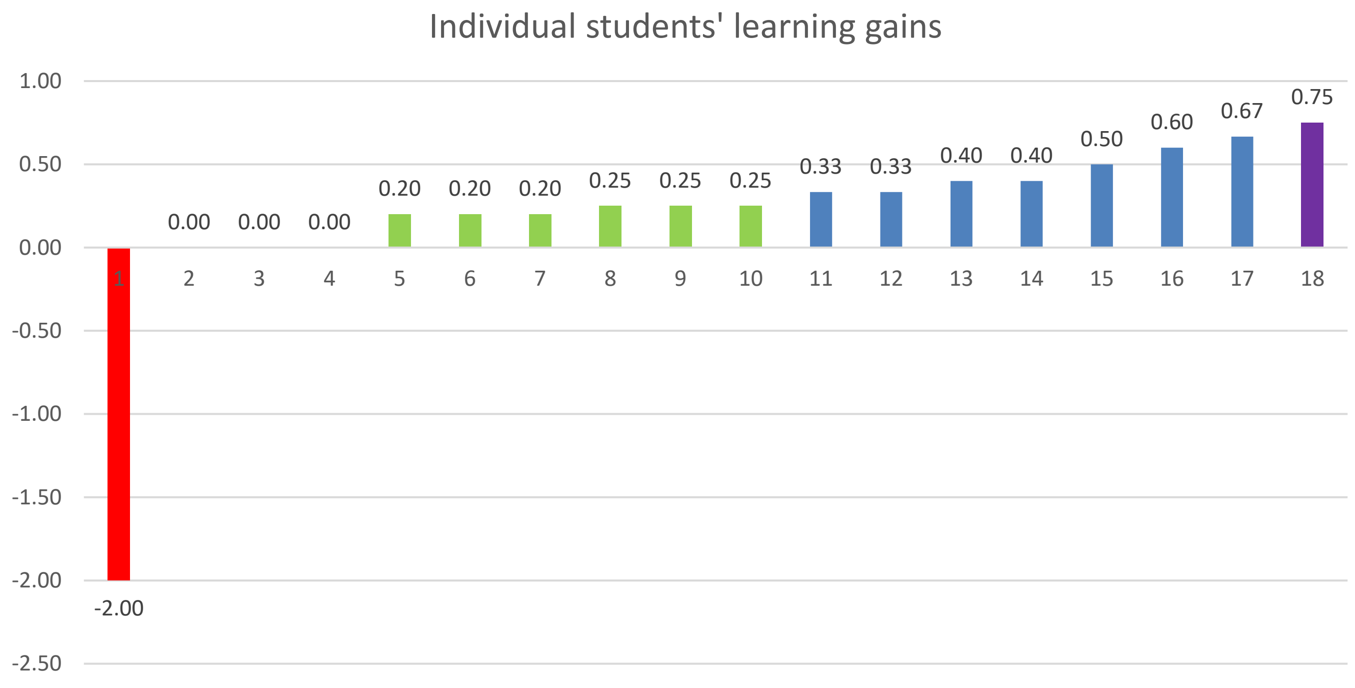

Figure 3. Distribution of the students' learning gains for the conceptual questions. Note that individual students are ordered according to their learning gain only in this respect.

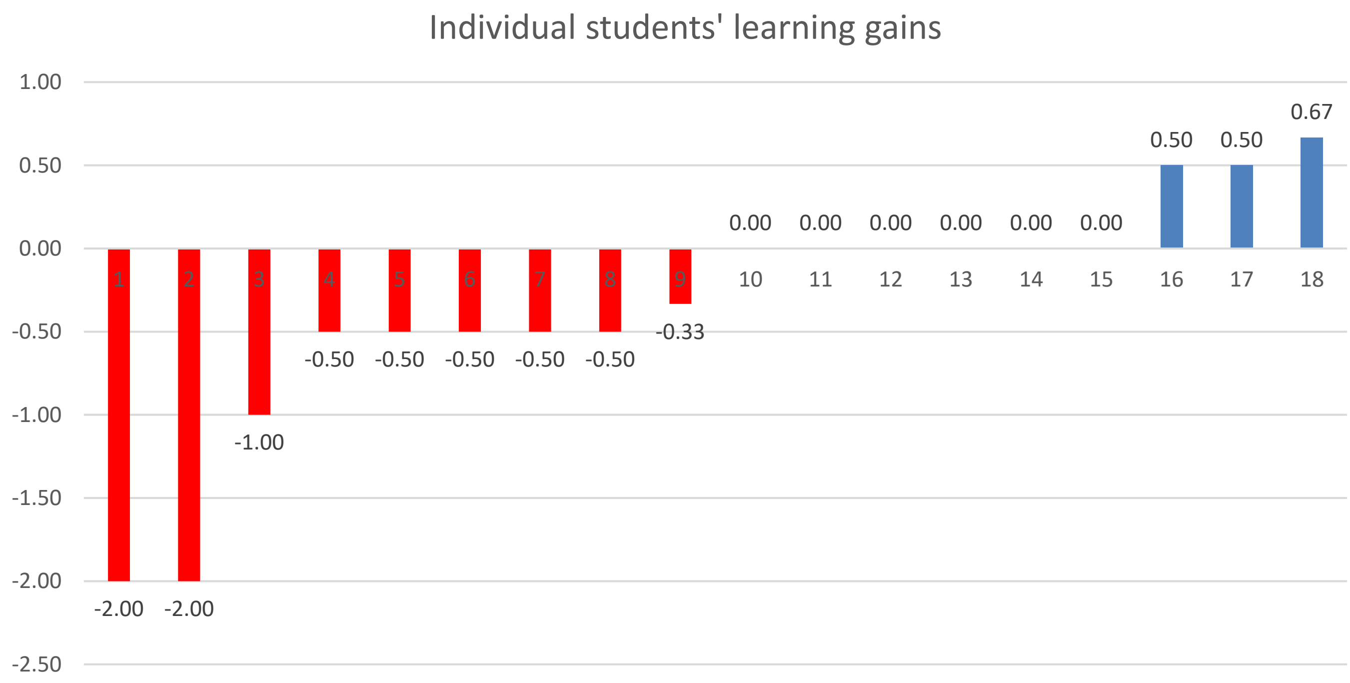

Figure 4. Distribution of the students' learning gains for the application questions. Note that individual students are ordered according to their learning gain only in this respect.

As can be seen in Table 4, a Wilcoxon signed-rank test confirms that the students achieved significantly greater learning gains for the conceptual questions than for the application questions, W = 125.500, p = .011, with effect size of 0.64. Based on the overall results, it is possible to answer the first research question that the students generally improved their scientific understanding after engaging in the design-based activity. However, in addressing to the second research question, they struggled with applying or transferring such understanding to new situations that differed from the situation involved in the design-based activity.

Table 4. Inferential results of the students' learning gains for diffrent types of questions.

Learning gains	**W**	**p**	**df**	**Effect size**
Conceptual questions vs. application questions	125.500	.011	17	0.64

6.4 Qualitative insights

Because students could choose whether they wished to explain the reasoning that led to their answers, many did not do so. Only one student—coincidentally, the one who exhibited the greatest improvement in learning—wrote out the calculations she used to arrive at her answer. Thus, she was purposively selected as an information-rich case to illustrate the difficulty she encountered in transferring her improved conceptual learning to real-life applications. For the conceptual questions, this student achieved high progression, with a learning gain of 0.75. However, she demonstrated moderate progression, with a learning gain of 0.50, for the application questions. As a result, the learning gains for each type of questions contributed to the total of her learning gain as high as 1.67 for all questions.

Regarding the six conceptual questions, she provided only two correct answers in the pre-test. Her reasons revealed that she had used the number-crunching strategy, by which she "combined the given numbers with arithmetic operation in non-canonical ways" (McGinn & Roth, 1998, p. 819), to arrive at the answers. For example, in the situation of item 10 illustrated in Figure 5, she answered that the mass of M would be 15 grams, based on the reasoning that "the spring balance is at [the position of] 6 and the 90-gram mass is at [the position of] 4," implying that she simply divided 90 by 6.

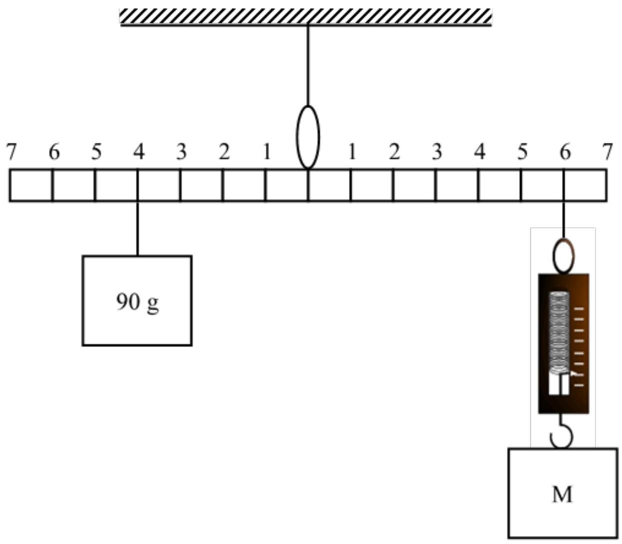

Figure 5. A conceptual question (adopted from McGinn & Roth, 1998, p. 823).

Following the design-based activity, she was able to arrive at the correct answer to this item based on the reasoning that "[the 60-gram mass] … creates an equal moment of force." In addition, she demonstrated the ability to calculate the moment of force on each side of the level: "90 x 4 = 360; 60 x 6 = 360." It is also evident in items 8 and 9 that she used a similar reasoning—that is, "because the net result is the equal moment of force (between two sides of the lever)"—to arrive at the correct answers. With this understanding, she improved her score of 5 for the conceptual questions. It was only item 6, which involved more than two forces acting on a lever, that she did not correctly answer. This incorrect answer indicated that she comprehended the concept of torque only in situations involving two forces acting on a lever.

Regarding the four application questions, this student was unable to provide any correct answers in the pre-test due to her lack of conceptual understanding regarding torque. As was the case when she answered the conceptual questions, she mainly relied on the number-crunching strategy (McGinn & Roth, 1998) to determine the answers to the conceptual questions. For example, in answering item 4, which asked the students to determine the minimum force required to lift a 120-newton television using an 8-meter-long lever (see Figure 6), she reasoned that “the television weighted 120 newtons and the level is 8 meters long (with) the pivot point at (the) 2-meter (position)”; thus, she calculated “(120 x 2)/8” to arrive the answer of 30 newtons.

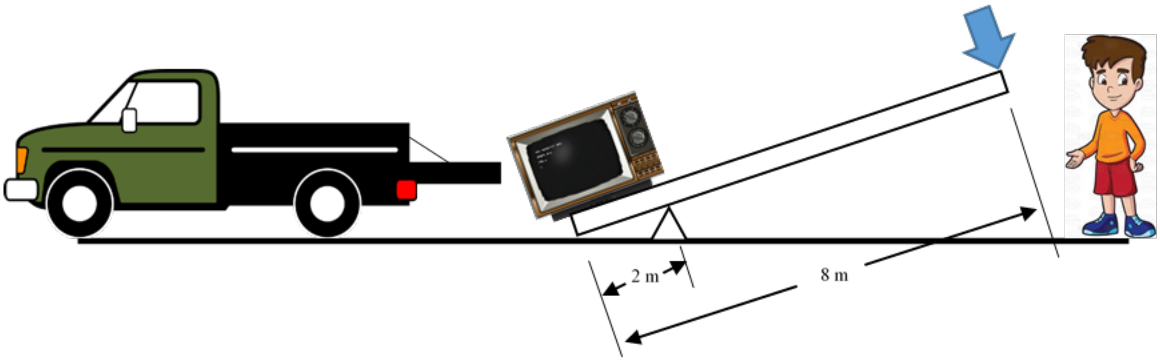

Figure 6. An application question (adopted from McKenna & Agogino, 1998, p. 444).

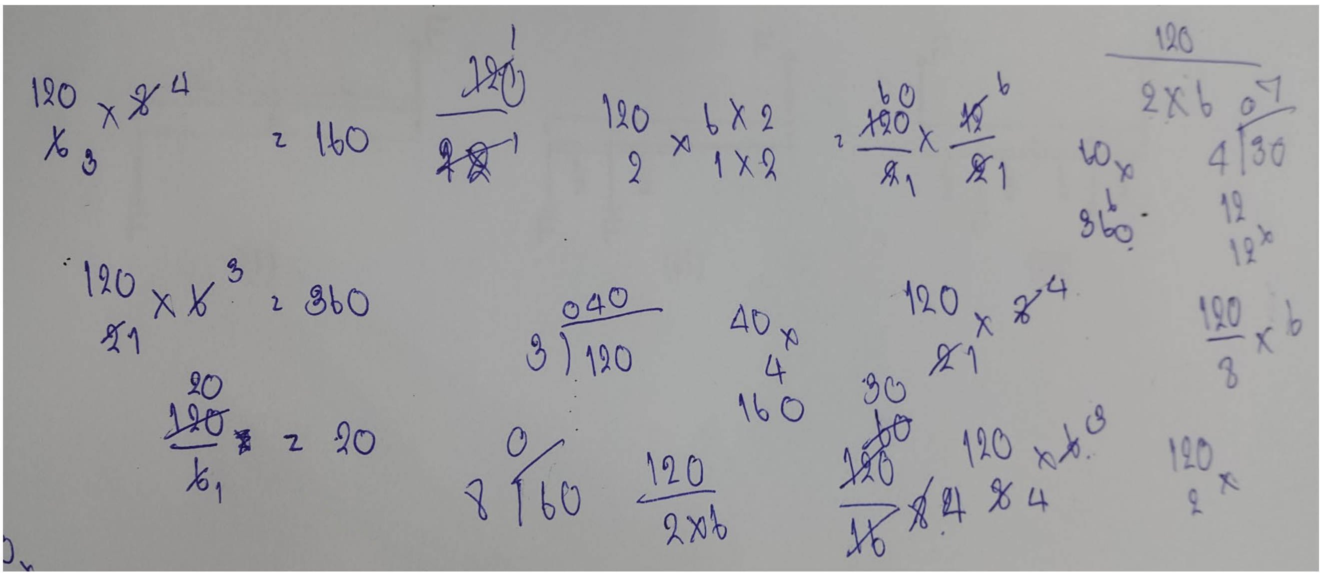

Figure 7. The highest-achieving student using the number-crunching strategy.

After the design-based learning intervention, in which this student considerably improved her conceptual understanding of torque, she was able to provide two correct answers to the four application questions in the post-test, indicating that she had achieved moderate progression. However, it is evident that she did not comprehend the concept of torque well enough to apply it in answering the application questions. In responding to item 4, for example, she failed to apply her scientific understanding, leading her to resort to the use of the number-crunching strategy again (see Figure 7).

7 Discussion

The current study demonstrates that, in the context of teaching and learning the concept of torque, a design-based activity can improve students' conceptual understanding. This result confirms that a design-based approach can be used to facilitate students' scientific understanding (Fortus et al., 2004). It also confirms that the design-based approach can support socioeconomically disadvantaged students in improving their science learning (Kolodner et al., 2003; Silk et al., 2009). The design-based approach has the potential to reduce the gap between students from high and low socioeconomic backgrounds (Mehalik et al., 2008). This positive result can be explained with reference to the way in which the design-based activity was conducted in the current study. Apedoe et al.'s (2008) model of design-based learning indeed allowed the students to use their prior ideas to initially design a table whose ability to support weight was tested. This might have provided them with an opportunity to reflect on those ideas and then receive empirical feedback. While designing, the students also had an opportunity to explore new ideas, whether by trial and error (Park et al., 2018), allowing them to notice and focus on critical aspects of the task (Chase et al., 2019; Malkiewich & Chase, 2019). This could have provided the students with the cognitive resources required to meaningfully conduct a scientific experiment, which in turn contributed to the improvement in their conceptual understanding. The results of this study, in which scientific inquiry was integrated into a design-based task, are also consistent with prior research indicating that hands-on activities (Kitrungloadjanaporn et al., 2018) as well as virtual simulations (Piyatissa et al., 2018) that provide students opportunities to experiment with torque and rotation can promote conceptual learning (Holzer & Andruet, 2000; Samuel et al., 2021).

However, despite the fact that they participated in the same activity, the students had different levels of learning gains. Although the data in the current study are too limited to fully explain the variations in the students' learning, this result can be broadly explained with reference to the fact that various factors could have influenced individual students' learning, such as prior knowledge (Schnittka & Bell, 2011), perceptions of the design-based activities (Schauble et al., 1991), levels of engagement (Wieselmann et al., 2020), social interactions within groups (Chusinkunawut et al., 2021), metacognition (Kavousi et al., 2020), and motivation (Smith et al., 2013). Specifically in the case of prior knowledge, Sarioglan and Kucukozer (2014) have noted a number of misconceptions related to torque and rotation that can potentially influence students' learnings; among these misconceptions are the beliefs that (1) equal forces cannot spin an object; (2) given two forces acting perpendicularly on a lever, the lever will rotate in the direction of the greater force regardless of where the forces act on the lever; and (3) given two equal forces acting perpendicularly on a lever at different distances from its pivot, the lever will rotate in the direction of the force closer to the pivot. Some of these misconceptions may result from confusion regarding the difference between force and torque, which can be found even among preservice physics teachers (Ozcan, 2017). Thus, the differences in terms of learning gains among the students in this study may partly be due to these misconceptions, which had not yet been addressed explicitly.

Additionally, McGinn and Roth (1998) have noted that the multiple-choice assessment is limited in terms of fully assessing students' scientific understanding; thus, it is likely that the test used in the current study could be a factor, especially for those low-achieving students who lacked mathematical knowledge and reading ability. Moreover, as the teacher played a crucial role in implementing the design-based activity (Capobianco et al., 2018), a confusion concerning the difference between clockwise and counterclockwise torque, as observed during the instruction, could be another factor. Additionally, the lever made from a meter ruler hung from a test-tube stand might not have been sufficiently accurate for the students to easily observe the relationship between the objects' weight and the distance between the objects and the hanging point. Altogether, the personal and contextual factors could contribute to and result in the variations in terms of learning gains exhibited by the students. Future research should focus more closely on students' experiences when engaging in design-based activities. For example, Wieselmann et al.'s (2020) study demonstrates that a conflict within a group of students can inhibit some of them from fully engaging and learning during design-based activities.

Despite the positive result regarding the improvement in the students' conceptual understanding of torque, it was more challenging for them to apply this improved understanding to real-life problems. This result is consistent with the results of Kelly and Sung's study (2017), which indicated that, while many students were successful in identifying a scientific concept they had learned in design-based activities, they had difficulties transferring that concept to new situations. It is also consistent with a study conducted by Dixon and Brown (2012), who found that only about 17% of participating students were able to apply the scientific knowledge they had learned in a design-based curriculum to solve new problems. The result also aligns with Apedoe et al.'s (2012) study showing that students who engaged in design-based learning performed best in no-transfer questions and performed worst in far-transfer questions; their performance in near-transfer questions was in between. However, this result is inconsistent with Gomez Puente and Kroesen's (2020) study, which reported that students were able to apply scientific knowledge gained in design-based projects. It is worth noting that this study and those by Kelly and Sung (2017), Dixon and Brown (2012), and Apedoe et al. (2012) were conducted at elementary or secondary levels; only Gomez Puente and Kroesen's (2020) study was conducted at the undergraduate level. Thus, students' ages, educational levels, maturity, and ongoing practice may be issues in transferring what they have learned in design-based activities.

The result regarding the students' difficulties in applying what they had learned in design-based activities in new situations can be explained with reference to the theory of learning transfer. According to Royer (1979), for learning transfer to occur, students must construct a coherent mental map and understand that the map is relevant to a particular situation (Gilbert et al., 2011). In this context, "coherent" means that "all components of the map are linked and not isolated, such that there is a meaningful whole" (ibid, p. 828). Given the need for both of these conditions to exist for learning to be transferred, it is likely that either the students had not yet constructed a mental map of torque that was sufficiently coherent to be applied or they did not see a connection between what they had learned about torque through the design-based activity and the application questions; alternatively, they may have failed to achieve both conditions (Simons, 1999). Specifically in the context of learning about torque, which involves multiple representations (e.g., texts, situational pictures, force diagrams, and mathematical equations), Chang et al. (2021) have noted that students' ability to transfer knowledge depends on their performance in translating between these representations. Moreover, the design-based activity in this study only involved gravitational forces acting downward on objects (e.g., a table or lever), while some of the application questions also involved forces acting in different directions. Thus, the differences between the situations featured in the design-based activities and those depicted in the application questions, as well as the multiple representations used in those situations, may have limited the students' ability to apply or transfer their conceptual understanding of torque.

8 Conclusion

Since STEM education has drawn increasing attention around the globe (Li et al., 2020), designed-based learning has been recommended as a pedagogical approach for teachers to implement in classrooms. To promote the adoption of this pedagogical approach, however, teachers must recognize that design-based learning is beneficial to their students' learning, especially in terms of what is mandated in the curriculum. In addition to research indicating the positive influence of the design-based approach on students' learning of science (Apedoe et al., 2008; Fortus et al., 2004; Schnittka & Bell, 2011), the current study confirms that design-based learning can improve scientific understanding among students who are socioeconomically disadvantaged (Kolodner et al., 2003; Mehalik et al., 2008; Silk et al., 2009). Nonetheless, it also demonstrates that the students struggled to apply such understanding to situations that differed from the learning situation (Apedoe et al., 2012; Dixon & Brown, 2012; Kelly & Sung, 2017). These results contribute to the existing literature that, despite the nature of design-based learning emphasizing the application of scientific knowledge in the engineering design process, the acquisition of scientific understanding does not occur simultaneously with or lead to learning to apply scientific understanding. Students, especially those who are socioeconomically disadvantaged, need more opportunities, and perhaps more scaffolding, to apply scientific understandings acquired in design-based activities to novel yet related situations.

9 Recommendations

The current study has implications for STEM education. As socioeconomically disadvantaged students can better understand a scientific concept after engaging in design-based learning, the design-based approach can make STEM education accessible for all students. In this regard, design-based learning is not only for advanced or advantaged students; it can also be regarded as a form of inclusive education. With suitable pedagogical practices, such as implementing it in a context relevant to students' everyday experiences, a design-based activity may support STEM learning for all students, including those who are socioeconomically disadvantaged. For the design-based approach to be effective, scaffolding strategies are crucial. While contrasting cases that allowed students to notice critical aspects of what they are designing (Chase et al., 2019) were used as scaffolding in this study, it is important to note that other forms of scaffolding can also be provided to students, such as the use of a design log with reflective prompts (Figliano & Wells, 2019), the use of demonstrations intended to explicitly challenge students' misconceptions (Schnittka & Bell, 2011), and the use of intermediary representations among multiple representations (Chang et al., 2021). Providing various opportunities and several kinds of scaffolding could better facilitate socioeconomically disadvantaged students in applying and transferring what they have learned during design-based activities to new situations. Therefore, future research should examine the effectiveness of these forms of scaffolding in facilitating students' ability to transfer knowledge gained in design-based learning.

10 Limitations

Some limitations need to be acknowledged. First, as the current study was conducted in a small school, a control group of students was not available. Some threats might inevitably affect the validity of the results. Second, as the data in the current study were mainly collected using a multiple-choice test, what the students learned during the design-based activity could not be fully described. Future research should be conducted in a manner that better ensures the validity of the results and describes the students' learning process more fully. Moreover, the design-based activity used in the current study needs to be refined for it to be more effective. Such refinement should be done in collaboration with teachers who are interested in implementing this design-based activity in their respective contexts.

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References

Apedoe, X. S., Ellefson, M. R., & Schunn, C. D. (2012). Learning together while designing: Does group size make a difference? *Journal of Science Education and Technology, 21*(1), 83–94. https://doi.org/10.1007/s10956-011-9284-5

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. https://doi.org/10.1007/s10956-008-9114-6

Arik, M., & Topcu, M. S. (2020). Implementation of engineering design process in the K-12 science classrooms: Trends and issues. *Research in Science Education*. https://doi.org/10.1007/s11165-019-09912-x

Bloom, B. S. (1965). *Taxonomy of educational objectives: The classification of education goals*. Michigan: David McKay Company.

Broer M., Bai Y., & Fonseca F. (2019) *Socioeconomic inequality and educational outcomes: Evidence from twenty years of TIMSS*. Cham: Springer.

Capobianco, B. M., DeLisi, J., & Radloff, J. (2018). Characterizing elementary teachers' enactment of high-leverage practices through engineering design-based science instruction. *Science Education, 102*(2), 342–376. https://doi.org/10.1002/sce.21325

Chang, J-Y., Cheng, M-F., Lin, S-Y., & Lin, J-L. (2021). Exploring students' translation performance and use of intermediary representations among multiple representations: Example from torque and rotation. *Teaching and Teacher Education, 97*, 103209. https://doi.org/10.1016/j.tate.2020.103209

Chase, C. C., Malkiewich, L., & Kumar, A. S. (2019). Learning to notice science concepts in engineering activities and transfer situations. *Science Education, 103*(2), 440–471. https://doi.org/10.1002/sce.21496

Chinn, C. A., & Malhotra, B. A. (2002). Children's responses to anomalous scientific data: How is conceptual change impeded? *Journal of Educational Psychology, 94*(2), 327–343. https://doi.org/10.1037/0022-0663.94.2.327

Chusinkunawut, K., Henderson, C., Nugultham, K., Wannagatesiri, T., & Fakcharoenphol, W. (2021). Design-based science with communication scaffolding results in productive conversations and improved learning for secondary students. *Research in Science Education. 51*(4), 1123–1140. https://doi.org/10.1007/s11165-020-09926-w

Creswell, J. W., & Plano Clark, V. L. (2011). *Designing and conducting mixed methods research*. California: SAGE Publications.

De Jong, T., & Ferguson-Hessler, M. G. M. (1996). Types and qualities of knowledge. *Educational Psychologist, 31*(2), 105–113. https://doi.org/10.1207/s15326985ep3102_2

Dixon, R. A., & Brown, R. A. (2012). Transfer of learning: Connecting concepts during problem solving. *Journal of Technology Education, 24*(1), 2–17. http://doi.org/10.21061/jte.v24i1.a.1

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), 103–120. https://doi.org/10.1002/j.2168-9830.2005.tb00832.x

Ellefson, M. R., Brinker, R. A., Vernacchio, V. J., & Schunn, C. D. (2008). Design-based learning for biology: Genetic engineering experience improves understanding of gene expression. *Biochemistry and Molecular Biology Education, 36*(4), 292–298.

https://doi.org/10.1002/bmb.20203

Falloon, G., Hatzigianni, M., Bower, M., Forbes, A., & Stevenson, M. (2020). Understanding K-12 STEM education: A framework for developing STEM literacy. *Journal of Science Education and Technology, 29*(3), 369–385. https://doi.org/10.1007/s10956-020-09823-x

Field, A. (2009). *Discovering Statistics Using SPSS*. California: SAGE Publications.

Figliano, F. J., & Wells, J. G. (2019). Evidencing STEM content knowledge transfer: Abstraction in technological/engineering design challenges. *Journal of Technology Education, 31*(1), 19–41. http://doi.org/10.21061/jte.v31i1.a.2

Fortus, D., Dershimer, R. C., Krajcik, J., Marx, R. W., & Mamlok-Naaman, R. (2004). Design-based science and student learning. *Journal of Research in Science Teaching, 41*(10), 1018–1110. https://doi.org/10.1002/tea.20040

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education, 27*(7), 855–879. https://doi.org/10.1080/09500690500038165

Gallagher, J. J. (2000). Teaching for understanding and application of science knowledge. *School Science and Mathematics, 100*(6), 310–318. https://doi.org/10.1111/j.1949-8594.2000.tb17325.x

Gilbert, J. K., Bulte, A. M. W., & Pilot, A. (2011). Concept development and transfer in context-based science education. *International Journal of Science Education, 33*(6), 817–837. https://doi.org/10.1080/09500693.2010.493185

Godwin, A., & Potvin, G. (2017). Pushing and pulling Sara: A case study of the contrasting influences of high school and university experiences on engineering agency, identity, and participation. *Journal of Research in Science Teaching, 54*(4), 439–462. https://doi.org/10.1002/tea.21372

Gomez Puente, S. M., & Kroesen, G. M. W. (2020). Facilitating retention and transfer of physics concepts with challenging assignments in design-based learning projects. *Open Journal of Social Sciences, 8*(12), 366–387. https://doi.org/10.4236/jss.2020.812030

Goss-Sampson, M. A. (2020). *Statistical analysis in JASP: A guide for students*. https://jasp-stats.org/wp-content/uploads/2020/11/Statistical-Analysis-in-JASP-A-Students-Guide-v14-Nov2020.pdf

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66*(1), 64–74. https://doi.org/10.1119/1.18809.

Han, S., Capraro, R., & Capraro, M. M. (2015). How science, technology, engineering, and mathematics (STEM) project-based learning (PBL) affects high, middle, and low achievers differently: The impact of student factors on achievement. *International Journal of Science and Mathematics Education, 13*(5), 1089–1113. https://doi.org/10.1007/s10763-014-9526-0

Holzer, S. M., & Andruet, R. H. (2000). Experiential learning in mechanics with multimedia. International *Journal of Engineering Education, 16*(5), 372–384.

Institute for the Promotion of Teaching Science and Technology. (2015). *Basic Knowledge about STEM Education*. http://www.stemedthailand.org/wp-content/uploads/2015/03/newIntro-to-STEM.pdf

Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a definition of mixed methods research. *Journal of Mixed Methods Research, 1*(2), 112–133. https://doi.org/10.1177/1558689806298224

Kavousi, S., Miller, P. A., & Alexander, P. A. (2020). Modelling metacognition in design thinking and design making. *International Journal of Technology and Design Education, 30*(4), 709–735. https://doi.org/10.1007/s10798-019-09521-9

Kellaghan, T. (2001). Towards a definition of educational disadvantage. *The Irish Journal of Education, 32*, 3–22.

Kelly, T. R., & Knowles, J. G. (2016). A conceptual framework of integrated STEM education. *International Journal of STEM Education, 3*(11). https://doi.org/10.1186/s40594-016-0046-z

Kelly, T., & Sung, E. (2017). Examining elementary school students' transfer of learning through engineering design using think-aloud protocol analysis. *Journal of Technology Education, 28*(2), 83–108. http://doi.org/10.21061/jte.v28i2.a.5

Kerby, D. S. (2014). The simple difference formula: An approach to teaching nonparametric correlation. *Comprehensive Psychology, 3*, Article 1. https://doi.org/10.2466/11.IT.3.1

Kitrungloadjanaporn, P., Phothong, A., & Precharattana, M. (2018). Seesaw balancing: A hands-on model to understand moment of force in classroom. *Applied Mechanics and Materials, 879*, 269–275. https://doi.org/10.4028/www.scientific.net/AMM.879.269

Kolodner, J. L., Camp, P. J., Crismond, C. D., Fasse, B., Gray, J., Holbrook, J., Puntambekar, S., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design™ into practice. *The Journal of the Learning Sciences, 12*(4), 495–547. https://doi.org/10.1207/S15327809JLS1204_2

Lewis, T. (2006). Design and inquiry: Bases for an accommodation between science and technology education in the curriculum? *Journal of Research in Science Teaching, 43*(3), 255–281. https://doi.org/10.1002/tea.20111

Li, Y., Wang, K., Xiao, Y., & Froyd, E. (2020). Research and trends in STEM education: A systematic review of journal publications. *International Journal of STEM Education, 7*(11). https://doi.org/10.1186/s40594-020-00207-6

Lobato, J., Rhodehamel, B., & Hohensee, C. (2012). "Noticing" as an alternative transfer of learning process. *The Journal of the Learning Sciences, 21*(3), 433–482. https://doi.org/10.1002/sce.21496

Malkiewich, L. J., & Chase, C. C. (2019). Focusing processes: Potential pathways for transfer of science concepts from an engineering task. *International Journal of Science Education, 41*(11), 1475–1495. https://doi.org/10.1080/09500693.2019.1613583

Marulcu, I, & Barnett, M. (2013). Fifth graders' learning about simple machines through engineering design-based instruction using LEGO™ materials. *Research in Science Education, 43*(5), 1825–1850. https://doi.org/10.1007/s11165-012-9335-9

McGinn, M. K., & Roth, W-M. (1998). Assessing students' understanding about levers: Better test instruments are not enough. *International Journal of Science Education, 20*(7), 813–832. https://doi.org/10.1080/0950069980200705

McKenna, A., & Agogino, A. (1998). A web-based instructional module for teaching middle school students engineering de-sign with simple machines. *Journal of Engineering Education, 87*(4), 437–444. https://doi.org/10.1002/j.2168-9830.1998.tb00376.x

Mehalik, M. M., Doppelt, Y., & Schunn, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education, 97*(1), 71–85. https://doi.org/10.1002/j.2168-9830.2008.tb00955.x

Morgan, G. A., Leech, N. L., Gloeckner, G. W., & Barrett, K. C. (2013). *IBM SPSS for Introductory Statistics*. New York: Routledge.

National Statistical Office. (2019). *Average monthly income/household (2019).* http://www.nso.go.th/sites/2014en

Norman, D. (2013). *The Design of Everyday Things. (Revised and expanded edition).* New York: Basic Books.

Novak, E. (2014). Effects of simulation-based learning on students' statistical factual, conceptual and application knowledge. *Journal of Computer Assisted Learning, 30*(2), 148–158. https://doi.org/10.1111/jcal.12027

Organisation for Economic Co-operation and Development. (2018). *Equity in education: Breaking down barriers to social mobility*. Paris: OECD Publishing.

Ozcan, O. (2017). Examination the preservice physics teachers' cognitive structure about the concept of "torque". *SHS Web of Conferences, 37*, 01050. https://doi.org/10.1051/shsconf/20173701050

Park, D., Park, M., & Bates, A. B. (2018). Exploring young children's understanding about the concept of volume through engineering design in a STEM activity: A case study. *International Journal of Science and Mathematics Education, 16*(2), 275–294. https://doi.org/10.1007/s10763-016-9776-0

Patton, M. Q. (2002). *Qualitative research and evaluation methods*. California: SAGE Publications.

Piyatissa, M, L. S., Johar, M. G. M., & Tarofder, A. K. (2018). Evaluating the effectiveness of a PhET simulation for teaching and learning of 'turning effect of force' in physics at secondary school level. *International Journal of Advanced Research and Publications, 2*(8), 32–39.

Promboon, S., Finley, F. N., & Kaweekijmanee, K. (2018). The evolution and current status of STEM education in Thailand: Policy directions and recommendations. In G. W. Fry (Ed.). *Education in Thailand: An old elephant in search of a new mahout* (pp. 423–459). Singapore: Springer. https://doi.org/10.1007/978-981-10-7857-6_17

Provincial Community Development Office of Chiang Rai. (2019). *A summary of basic-needs information at village levels in Chiang Rai in 2019*. https://chiangrai.cdd.go.th/wp-content/uploads/sites/14/2019/07/0019.3-_%E0%B8%A717288.pdf

Quinn, C. M., Reid, J. W., & Gardner, G. E. (2020). S + T + M = E as a convergent model for the nature of STEM. *Science and Education, 29*(4), 881–898. https://doi.org/10.1007/s11191-020-00130-w

Rimoldini, L. G., & Singh, C. (2005). Student understanding of rotational and rolling motion concepts. *Physical Review Special Topics - Physics Education Research, 1*, 010102. https://doi.org/10.1103/PhysRevSTPER.1.010102

Royer, J. M. (1979). Theories of the transfer of learning. *Educational psychologist, 14*(1), 53–69. https://doi.org/10.1080/00461527909529207

Samuel, C. K., Cosmas, R., & Dinah, S. C. (2021). Improving students' application of moment of force concepts in physics through experimental approach, a case of secondary schools in Marakwet West Sub-Country, Elgeyo Marakwet Country, Kenya. *African Journal of Education, Science and Technology, 6*(2), 236–244.

Sarioglan, A. B., & Kucukozer, H. (2014). 11th grade students' conceptual understanding about torque concept: A longitudinal study. *Eurasia Journal of Physics and Chemistry Education, 6*(2), 162–175.

Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching, 28*(9), 859–882. https://doi.org/10.1002/tea.3660280910

Schnittka, C., & Bell, R. (2011). Engineering design and conceptual change in science: Addressing thermal energy and heat transfer in eighth grade. *International Journal of Science Education, 13*(1), 1861–1887. https://doi.org/10.1080/09500693.2010.529177

Silk, E. M., Schunn, C. D., & Cary, M. S. (2009). The impact of an engineering design curriculum on science reasoning in an urban setting. *Journal of Science Education and Technology, 18*(3), 209–223. https://doi.org/10.1007/s10956-009-9144-8

Simons, P. R. J. (1999). Transfer of learning: Paradoxes for learners. *International Journal of Educational Research, 31*(7), 577–589. https://doi.org/10.1016/S0883-0355(99)00025-7

Smith, J. L., Lewis, K. L., Hawthorne, L., & Hodges, S. D. (2013). When trying hard isn't natural: Women's belonging with and motivation for male-dominated STEM fields as a function of effort expenditure concerns. *Personality and Social Psychology Bulletin, 39*(2), 131–143. https://doi.org/10.1177/0146167212468332.

University of Colorado. (2020). *Balancing Act*. https://phet.colorado.edu/en/simulation/balancing-act.

Vattam, S. S., & Kolodner, J. L. (2008). On foundations of technological support for addressing challenges facing de-sign-based science learning. *Pragmatics and Cognition, 16*(2), 406–437. https://doi.org/10.1075/pc.16.2.08vat

Verdugo, J. J., Solaz-Portoles, J. J., & Sanjose, V. (2016). Pre-service primary school teachers' science content knowledge: An instrument for its assessment. *International Journal of Innovation in Science and Mathematics Education, 24*(2), 37–51 https://openjournals.library.sydney.edu.au/index.php/CAL/article/view/10322.

Wang, T., & Andre, T. (1991). Conceptual change text versus traditional text and application questions versus no questions in learning about electricity. *Contemporary Education Psychology, 16*(2), 103–116. https://doi.org/10.1016/0361-476X(91)90031-F

Wannagatesiri, T., Nukultham, K., Kruea-In, N., & Thongperm, A. (2014). Lesson learned from the experiences of small schools in Thailand. *Procedia – Social and Behavioural Sciences, 141*, 1095–1100. https://doi.org/10.1016/j.sbspro.2014.05.184

Wendell, K. B., & Lee, H. (2010). Elementary students' learning of materials science practices through instruction based on engineering design tasks. *Journal of Science Education and Technology, 19*(6), 580–601. https://doi.org/10.1007/s10956-010-9225-8

White, D., & Delaney, S. (2021). Full STEAM ahead, but who has the map? – A PRISMA systematic review on the incorporation of interdisciplinary learning into schools. *LUMAT: International Journal on Math, Science and Technology Education, 9*(2), 9–32. https://doi.org/10.31129/LUMAT.9.2.1387

Wieselmann, J. R., Dare, E. A., Ring-Whalen, E. A., & Roehrig, G. H. (2020). "I just do what the boys tell me": Exploring small group student interactions in an integrated STEM unit. *Journal of Research in Science Teaching, 57*(1), 112–144. https://doi.org/10.1002/tea.21587.

Yu, K-C., Lin, K-Y., & Fan, S-C. (2015). An exploratory study on the application of conceptual knowledge and critical thinking to technological issues. *International Journal of Technology and Design Education, 25*(3), 339–361. https://doi.org/10.1007/s10798-014-9289-5