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The Role of Digital-Media-Based Pedagogical Aids in Elementary Entomology: An Innovative and Sustainable Approach

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Abstract: It has been challenging for city school pupils to learn about insects, given the lack of live insects. To overcome this challenge, the objective of this study is to propose the use of emerging digital media, namely three-dimensional printing (3DP) technologies, to create reusable, fake, "live" insects. In this study, we designed two 3D-printed pedagogical aids to support elementary entomology. The first aid was a set of cards showing photos of the 3D-printed insect prototype, which could help the learners in close observation of the insect body's regions and parts, and the second 3D-printed aid was a construction kit mimicking physical insects, which were made of an enlarged 3D-printed insect prototype. The two aids were used in our field experiment to examine the effectiveness in learning and motivation. A total of 153 pupils were grouped into three groups (one using the existing multimedia e-book, one using the first 3DP aid, and one using the second aid). The results confirm that the digital media application—in this case, 3DP technologies—were able to compensate for the lack of the live insects. These results raised our confidence in using a customized size 3D-printed insect prototype to enhance rudimentary entomology inside the classroom. If the 3DP technologies are used properly, they could offer an innovative and sustainable solution.

Keywords: digital media; innovative pedagogical aids; sustainable solutions for elementary learning; 3D-printed insect prototype; learning motivation; learning achievement

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1. Introduction

Learning about insects has become an important lesson in natural science classes in elementary schools because they play an important role in maintaining environmental sustainability through their activities, such as pollinating plants and recycling waste [1]. Research has shown that the use of live insects in natural science classes effectively enhances subject learning [2–4]. This is because pupils can look at the insects or even touch them. These direct, close observations [4] and hands-on investigations [2] are able to create a closer human–insect interaction. However, city schools usually have limited access to live insects [5,6], which help to visualize and build their knowledge of the insects that they rarely see in real life [7,8]. In order to overcome this limitation, alternatives to live insects have been developed. For example, two-dimensional illustrations (pictures or photos) of insects have been used. Despite the fact that these alternatives are shown to enhance children's learning behavior and experiences [9,10], they still suffer a critical limitation: experiences in close observation and sense of touch are absent [4]. Therefore, an innovative teaching aid that makes these experiences possible is needed. Modern development in digital media makes this possible.

The increasing availability of 3D design software and the rapid development of low-cost 3D printers make 3DP particularly promising to be used in education [11–13]. The 3D digital models from the software can produce durable replicas through 3D printers that are almost identical to real objects [14–16]. Digital models are reusable, customizable, and scalable. Furthermore, one of the materials, i.e., PLA (polylactic acid), used for the materials of 3D-printed replicas, is more sustainable and environmentally friendly than traditional plastics [17,18]. Previous studies have investigated the use of 3D-printed high-fidelity replicas as an alternative for authentic objects, for example, organs, multicellular animals, and geometries [15,16,19,20]. The three-dimensional printing (3DP) replicas could increase pupils' learning motivation, and more importantly, improve retention of the knowledge they obtained via learning with 3DP replicas [19,21–23]. The use of 3DP has shown the potential for enhancing learning outcomes [19,24].

There are two practical challenges that teachers and schools face in using 3D-printed replicas. First, a high-fidelity replica representing a life-sized insect requires high-end equipment that is expensive to acquire, and this expense becomes a barrier for many schools to adopt this type of equipment. While the 3DP replicas can be obtained from other sources, these replicas present the second challenge: a life-sized insect replica is so small that learners would be unable to handle and manipulate it with ease. Therefore, this research proposed an innovative alternative: an enlarged 3DP single-color prototype that is created with low-cost 3D printers. This low-cost of 3DP technology makes it possible for schools to adopt; however, whether or not this approach is able to enhance learning about insects is not yet known. However, a 3DP prototype may not be always available for each class, therefore this study investigates if the 2D illustration of the 3D-printed prototypes could have some value. Though these cards were not as real as the 3D-printed prototypes in materializing the authentic insect, they were developed because the 3D-printed prototypes are not yet available in most classrooms.

The major objective of this research was to create two learning aids for natural science learners at elementary schools: (1) the 3D insect prototypes and (2) a set of photo cards (i.e., photos of the 3D insect prototypes). These two aids were used in a field experiment to investigate their ability to improve learners' learning achievement and learning motivation. The following hypotheses were proposed:

Hypothesis 1. *3D insect prototypes are the most effective learning aid in terms of achievement and motivation.*

Hypothesis 2. *Photos of the 3D insect prototypes are better than existing traditional e-book learning aids in terms of achievement and motivation.*

2. Materials and Methods

2.1. Stimuli Development

We selected the related subject course to test each of the learning materials. The selected course was called "Understanding Insects" (see Appendix A). There were three types of learning materials: insect prototypes, photo cards, and a multimedia e-book. Insect prototypes and photo cards were developed for the purpose of this study, while the multimedia e-book was selected from one of the three major publishers, Hanlin Publishers. The reason for using the multimedia e-book for the control group was that this type of material is commonly used as a supplemental material by teachers to support the learning of various topics at schools in Taiwan. The teaching and learning procedures remained consistent throughout the three groups; the only difference was the learning materials used in the different groups. All three groups had the same teacher.

2.1.1. Insect Prototype

Two types of insect prototype were developed: the fixed insect prototype (see Figure 1) and the assembled insect prototype (see Figure 2). With the insect prototypes, the learners were able to repeat the assembly and observe and compare the body parts of the 3DP prototype. The insect prototypes were produced by following the five steps outlined by Garcia et al. [25]: (1) insect selection, (2) creation of 3D geometry, (3) file optimization for printing, (4) selection of 3D printer, and (5) selection of 3DP filament material. Six insects most commonly used in natural science learning were selected, namely, ant, bee, beetle, butterfly, grasshopper, and mantis. A 3D design software, named Meshmixer CAD, was used to design 3D puzzle components including head, thorax, abdomen, antenna, legs, and wings (see Figure 3). The low-cost printer was provided to the learners' school, Long Pu Elementary School, Taiwan, and cost under 2000 US dollars.

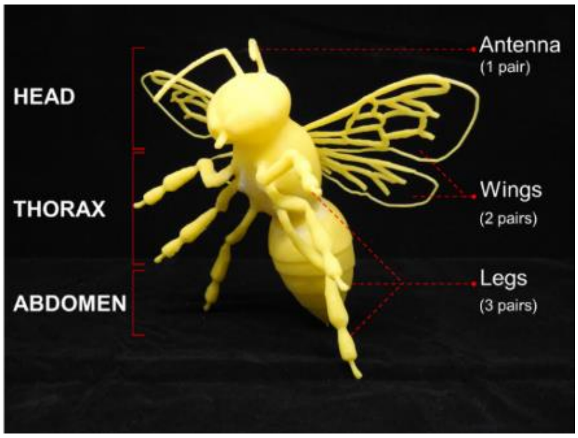
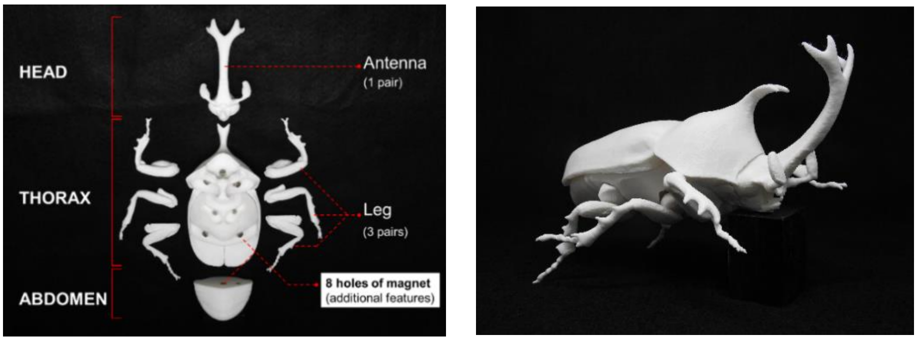


Figure 1. A fixed insect prototype, using a monochrome yellow bee as an example.



(**a**) (**b**)

Figure 2. The assembled insect prototype, using a white beetle as an example: (**a**) component parts of assembled insect prototype; (**b**) complete assembled insect prototype.

To ensure that assembly can be easily completed, the models were created at 10 times larger than actual size. In addition, the assembled parts contained magnets at their ends, so the line-up magnets in all body part components allowed easy assembly and disassembly. A typically assembled replica had twelve holes in which two holes were on the head for two antennas, six holes on the bottom side of the thorax for six legs, and four holes on the back side of the thorax for four wings (see Figure 3). The holes were circle-shaped with a radius of 5 mm and a depth of 2 mm. The completed designs of the insect prototype and its component parts were then input into a 3D printer using 1.75 mm PLA, a robust but biodegradable plastic material, and the complete models were printed in yellow with the component parts in white. Magnet fasteners were installed in the printed components, which were tested for proper assembly.

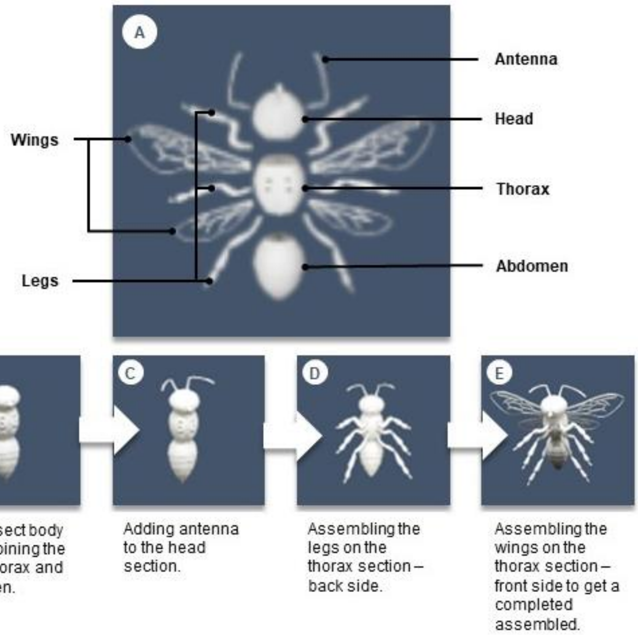


Figure 3. One potential way to assemble the component parts of a bee. (**A**) the component parts of a bee; (**B**) building the insect body; (**C**) adding antenna; (**D**) assembling the legs; (**E**) assembling the wings.

2.1.2. Photo Card

Photographs of the 3D insect prototypes were printed on A4 paper and laminated. The photographs were taken to clearly show the models and were displayed with each insect's body structure. Each insect was presented with two views, i.e., top and ventral views in order to demonstrate the details of the body parts. The photographs allowed learners to observe the images of insect prototypes.

2.1.3. Multimedia E-Book

The multimedia e-book was provided by the publisher and was developed only for school teachers. School teachers could display the content through the classroom's projector. The visual insect content was displayed with the real insect image, viewed from the front, back, left, or right.

2.2. Procedure

In order to investigate whether each learning aid would enhance learning outcomes, an experimental approach was adopted. The experiment contained three groups [26] (see Figure 4): one control group that used a traditional e-book to learn about insects and two experimental groups, with one using insect prototypes and the other using photo cards of the 3DP insect prototypes. The participants were recruited from six classes of fourth graders aged 9–10 at Long Pu Elementary School, Taipei, Taiwan. Selection of the six classes was decided upon the agreement of the class tutor. All of the pupils of each class who took the pre-test completed the course. The selection of the two classes for each group was decided based on the available sampling featured as quasi-experimental research [27]. The experiment was conducted in the classroom as part of the natural science course.

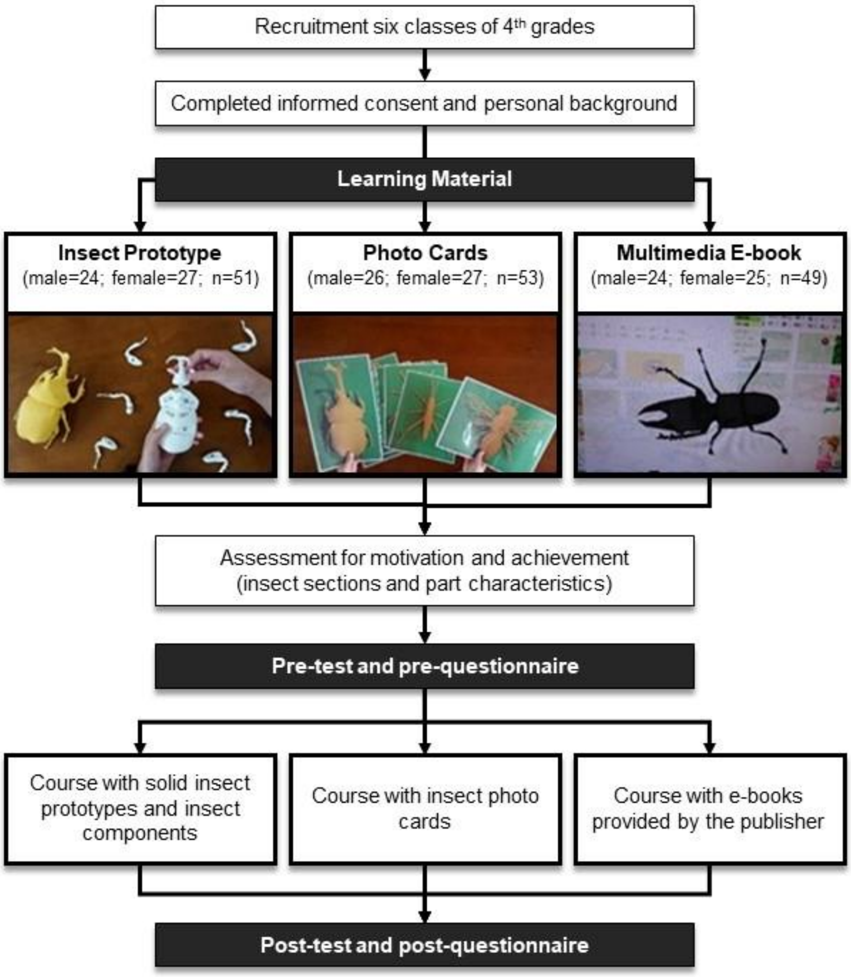


Figure 4. Experimental procedures.

The teaching and learning procedures followed the related subject course "Understanding Insects", following the Science and Life Technology Curriculum Standard for 1st to 9th grades, Ministry of Education, Taiwan. Specifically, these activities aimed to enhance the learners' ability to identify the anatomy of insects and to reduce the production of incorrect knowledge that had been observed in past learning. The course lasted for forty minutes and belonged to the second of the twelve lessons on elementary entomology. To achieve the learning objectives, the class proceeded in the following sequence: (1) The learners were encouraged to make predictions before the instructor presented the complete insects; (2) these predictions were then compared to the correct answers and discussed among pupils; then, (3) actual examinations of the pedagogical aids containing the insects took place. Throughout the course, instructors used quizzes to ensure that the core concepts of the course were correctly and interestingly learned. Therefore, each group took one of the six insects as its subject matter.

The learners' motivation and their knowledge about the insects were recorded the week prior to the first lesson in the experiment (pre-tests). The first lesson began with a warm-up of the students' background knowledge and a brief introduction of the upcoming activities using PowerPoint. The duration of this lesson lasted for a total of 40 min and covered four learning activities: course introduction and background knowledge review (5 min), familiarization with the core learning content and drawing (15 min), observation and manipulation of insect models and components (10 min), and questions and answers (10 min). The week after the insect lesson, these learners' motivation and their knowledge about the insects taught in the lesson were again recorded (post-tests).

In the insect prototype group, teams were randomly assigned with one out of six fixed and assembled insect prototypes. Members of each team were asked to carefully observe the 3DP insect prototype. Next, one member of each team was asked to draw the observed insect on a small whiteboard. After that, another member of the team labeled the drawing with the various sections and parts. The members of each team were asked to assemble the 3D assembly components into a completed insect. During the activities, the instructor also advised learners to carefully observe each part of the 3DP insect replica, guiding the learners to correctly label the various parts. The instructor then led the whole class to summarize the core concepts and finally presented a short quiz. The photo card group followed the same activities as the insect prototype group except that each team was provided with an A4 photograph of the completed insect model. For the multimedia e-book group, learners observed the image of the insect projected from the e-book while one team member drew the insect on a small whiteboard. Learners were then instructed on the insect's sections and arrangement of its parts including antenna, head, thorax, abdomen, legs, or wings. Once the pupils had finished drawing the insect, the instructor used e-book contents to display the front and the ventral side of the insects and helped pupils verify and correct their work. Finally, the instructor summarized the core concepts in the e-book and had the pupils complete a quiz.

2.3. Measures & Analysis

A chi-squared test was used to compare gender differences and group differences. The outcome measures of this research were knowledge, motivation, and subjective opinions. As for the knowledge, the quiz was designed based on the table of specifications (TOS) [28] using Bloom's taxonomy to evaluate learners' overall understanding of the insect sections and parts. Learner motivation was assessed using a questionnaire adapted from the ARCS Model of Motivation [29], including 28 questions related to attention, relevance, confidence, and satisfaction (see Appendix B). In regard to the subjective opinions, the written responses of one open-ended question assessing learners' learning experience were analyzed by two assistant researchers. The responses were cross-checked to acquire participants' subjective opinions in terms of a positive learning experience.

An independent t-test was used to compare learners' pre- and post-test performance for the various groups. Each pre-test and post-test had 5 true-or-false questions, 5 multiple choice questions, and two drawing exercises for a full score of 100 points. All statistical tests were two-tailed, and a p-value below 0.05 indicated statistical significance. Statistical analyses were performed with SPSS v.20.0 (IBM Corp., Armonk, NY, USA).

Two ANOVA analyses were carried out to ensure that the pupils held similar subject knowledge and motivation in each group prior to experimental manipulations. The results confirmed that the pupil participants had similar levels of subject knowledge across gender ($p > 0.50$) and across three groups ($p > 0.50$).

3. Results

As shown in Table 1 (gender) and Table 2 (knowledge and motivation), the baseline information distribution revealed no significant differences between the insect prototype, photo card, and multimedia e-book groups in terms of gender, pre-test knowledge, and pre-test motivation.

Table 1. Distribution of participant characteristics (ANOVA).

Classification	Insect Prototype (n = 51)		Photo Card (n = 53)		Multimedia E-Book (n = 49)		p-Value
	n	%	n	%	n	%	
Boys	24	47.06	26	49.06	24	48.98	0.730
Girls	27	52.94	27	50.94	25	51.02	0.651

Insect prototype group (class: 401,407); photo card group (class: 404,408); multimedia e-book group (class: 402,405).

Table 2. Pre-test comparison of learning knowledge and ARCS learning motivation (ANOVA).

Variable	Classification	Insect Prototype (*n* = 51)	Photo Card (*n* = 53)	Multimedia E-Book (*n* = 49)	Overall	Insect Prototype vs. Photo Card	Photo Card vs. Multimedia E-Book	Insect Prototype vs. Multimedia E-Book
		Mean ± SD	Mean ± SD	Mean ± SD	*p*-Value	*p*-Value	*p*-Value	*p*-Value
Knowledge	Overall	66.02 ± 2.621	65.94 ± 1.806	62.39 ± 2.830	0.493	1.000	0.911	0.894
Motivation	Overall	3.91 ± 0.71	3.66 ± 0.64	3.90 ± 0.66	0.103	0.173	0.230	1.000

Insect prototype group (class: 401,407); photo card group (class: 404,408); multimedia e-book group (class: 402,405).

3.1. Three Group Learning Knowledge and Motivation

As shown in Table 3, the three groups showed significant differences in terms of post-test performance, with the insect prototype group scored significantly higher than the multimedia e-book group ($p < 0.05$). However, no significant differences were found between the insect prototype vs. photo card groups and the insect prototype vs. multimedia e-book groups. Furthermore, for the comparison of post-test motivation among the three groups, the overall score in the motivation of the three groups was revealed to be significantly different ($p = 0.001$). By comparing two groups, the insect prototype group was significantly higher than the photo card group ($p < 0.05$) and the multimedia e-book group ($p = 0.001$). However, there were no significant differences between the photo card group and the multimedia e-book.

Table 3. Post-test comparison of learning knowledge and ARCS learning motivation (ANOVA).

Variable	Classification	Insect Prototype (*n* = 51)	Photo Cards (*n* = 53)	Multimedia E-Book (*n* = 49)	Overall	Insect Prototype vs. Photo Cards	Photo Cards vs. Multimedia E-Book	Insect Prototype vs. Multimedia E-Book
		Mean ± SD	Mean ± SD	Mean ± SD	*p*-Value	*p*-Value	*p*-Value	*p*-Value
Knowledge	Overall	89.37 ± 1.662	84.17 ± 1.426	82.71 ± 2.403	0.031	0.140	1.000	0.039 *
Motivation	Overall	4.20 ± 0.55	3.88 ± 0.57	3.77 ± 0.63	0.001 **	0.019	1.000	0.001 **

Insect prototype group (class: 401,407); photo card group (class: 404,408); multimedia e-book group (class: 402,405). * $p < 0.05$; ** $p < 0.01$.

3.2. Pre-Post Comparison Learning Knowledge and Motivation

As shown in Table 4, scores in knowledge increased significantly between the pre-test and post-test for all groups ($p < 0.001$). As shown in Table 4, motivation scores increased significantly in pre- and post-comparison in the insect prototype and photo card groups ($p < 0.01$). However, there were no significant differences in the multimedia e-book group.

Table 4. Comparison of pre-test and post-test ARCS learning motivation (paired *t*-test).

Category		Insect Prototype (*n* = 51)			Photo Card (*n* = 53)			Multimedia E-Book (*n* = 49)		
		Mean	SD	*p*-Value	Mean	SD	*p*-Value	Mean	SD	*p*-Value
Knowledge	Pre-test	66.02	(2.62)	0.000 ***	65.94	(1.81)	0.000 ***	62.39	(2.83)	0.000 ***
	Post-test	89.37	(1.66)		84.17	(1.43)		82.71	(2.40)	
Motivation	Pre-test	3.91	(0.71)	0.002 **	3.66	(0.64)	0.005 **	3.90	(0.66)	0.142
	Post-test	4.20	(0.55)		3.88	(0.57)		3.77	(0.63)	

Insect prototype group (class: 401,407); photo card group (class: 404,408); multimedia e-book group (class: 402,405). ** $p < 0.01$; *** $p < 0.001$.

3.3. Learners Perception

All subjects (153 participants) in the three groups completed the one open-ended question. After the content analysis, five specific items related to positive learning experience were extracted. As shown in Figure 5, the insect prototype group subjects cited the following as the most engaging parts of the learning experience: insect replica assembly (47%, 24 respondents), observing the insect replica (32%, 16), and drawing (14%, 7). By contrast, pupils in the photo card group cited observing (40%, 21) and drawing (11%, 6 respondents) as being the most engaging activities, while the multimedia e-book group cited observing (16%, 8) and drawing (4%, 2 respondents).

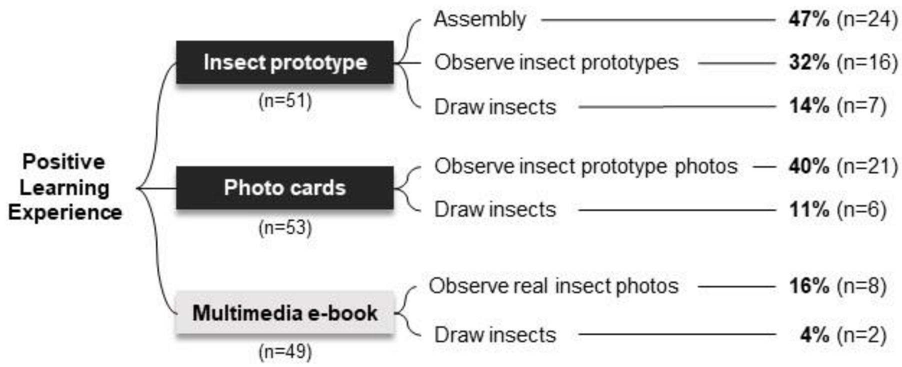


Figure 5. Subjective responses.

4. Discussion

Learning about insects has become more and more important in many elementary schools, given the vital role insects play in the ecosystem. Learners in cities encounter the challenge of not being able to see live insects. The following sections discuss the role of 3DP in elementary entomology.

4.1. Elementary Entomology Using 3DP

4.1.1. Knowledge

Using a field experiment, this study empirically verified the importance of the pedagogical aids. The results suggest that different aids significantly impact learning knowledge. Participants using the 3DP aids (the insect prototype and the photo card) performed the best in the post-learning quizzes and this result indicates the usefulness of using the 3DP aids for learning. The insect prototype group outperformed ($p < 0.05$) the multimedia e-book group on the post-test, suggesting that the learning aids may enhance learning in specific ways, for example, effectively increasing short-term memory. The potential reason is that the construction kits are able to support learning through play, which is helpful to the development of mental skills, such as making observations, concentration, and forming parts into a whole object [30,31]. Research has shown the importance of handling, touching, and playing with live insects in learning effectiveness [2]. Moreover, Shepardson [4] suggested that providing pupils with opportunities to observe and identify body regions and parts of insects was essential to enhancing their understanding of insect characteristics. Previous research addressed concerns that middle graders tend to have misconceptions about insects' body structure [32], i.e., mistaking an insect's legs as being attached to its abdomen rather than to its thorax, and being unable to differentiate insects from arthropods [4]. In the learning process, pupils were likely to group organisms (e.g., insects and arthropods) through observable features such as body regions and parts [33]. Therefore, applying physical learning aids, i.e., physical manipulatives, might add an additional benefit.

It is noteworthy that the effects of gaining knowledge through the use the photo cards was similar to that achieved through using the insect prototype. Our results were different from the finding in molecular structures in the chemistry domain. For example, Penny et al. [34] found that learners viewed 3D physical manipulatives as an improvement over 2D images. Future investigations should seek to identify factors that contribute to the enhancement effect on each pedagogical aid.

4.1.2. Motivation

Previous research has demonstrated the importance of motivation in education, for example, factors of ARCS motivation in perceived attention, perceived relevance, and perceived confidence directly positively influence students' attitudes toward competency development [35]. Our results show that only the insect prototype group was highly motivated. The results indicate that completing physical manipulatives may have encouraged pupils' concentration and self-confidence [36]. Additionally, the lack of significant improvement by the multimedia e-book group in terms of pre- and post-activity performance might be explained by the fact that the class was conducted in a typical classroom instruction fashion and thus produced no difference in motivation.

4.1.3. Subjective Opinion

Students' perceptions of learning are critical in determining the quality of the learning outcome [37]. The participants in the insect prototype group reported being engaged by the activities of assembling insect components, observing the physical prototype, and drawing insects. Furthermore, engagement was highest for assembling insect components, and since neither the learning aids in the photo card group or control group have such capabilities, engagement and thus learning motivation in the insect prototype group may have been driven by the ability to assembled the insects' prototypes. Assembly and disassembly activities may have helped elementary school pupils familiarize themselves with insect body parts, as the 3DP insect prototypes allowed the experience of touching and seeing insects in a way that resembles observing the real-life insects and in a way that the photo card group and control group were unable to do. For example, the participants in the photo card group cited the most engaging activity as the observation of the insect model photographs, and the results of this study indicate that, although these photos were helpful, they were not as helpful as the ability to assemble and dismantle insect body parts as in the construction kit. This may be because hands-on activities were particularly crucial for learners in this age group [38] but further validation of what factors would affect learners' perceptions about learning insects is still required.

4.2. The Role of Digital Media-Based 3DP Application in Learning

While the entomological knowledge of all three groups improved significantly ($p < 0.05$), the insect prototype and the photo card group outperformed the multimedia-e group using the traditional learning aid. Although the performance was similar between the insect prototype group and the photo card group, the results showed that the insect prototype group scored highest on learning motivation. This might have been because the learners in this group were able to go through the hands-on experience by touching and interacting with the insects' prototypes. Physical manipulatives are any concrete objects that allow learners to explore an idea in an active, hands-on approach. In addition, physical materials, such as puzzles or assembly components, are seen as facilitating learners in constructing knowledge through interaction with physical objects [39]. Applying physical manipulatives in the learning process has shown some potential benefits, such as enhanced learning motivation [19], better retention of knowledge [23], and improved knowledge acquisition and structural conceptualization [34,40], which led to improved learning outcomes [19,24]. Physical manipulatives to support learning have long been used; however, the common issues are in availability, such as building cost, productivity, and mobility.

Nowadays, 3DP is becoming popular for use in the education field. 3DP can be an alternative to developing physical manipulatives, i.e., imitating objects, in a fast and customizable way. 3DP technology in making physical manipulatives has shown some potential. Apart from entomology, extant studies have investigated the use of 3DP to support domain-specific knowledge acquisition, such as complex 3D atomic models in chemistry [41] and customized product design in footwear [42], as well as abstract concepts, such as audio frequencies in physics [16,23,41]. Costello et al. [20] used high-fidelity replicas to introduce the concept of ventricle septal defects. The advantages of 3D-printed artifacts relative to virtual, screen-based artifacts include improved tactility and interaction [43,44]. In the aspect of cost effectiveness, Griffith et al. [45] estimated that using 3DP in grasping molecular structures in chemistry would cost less than 20% of the price of commercially available artifacts. Finally, an added advantage is that free 3D digital geometries are made widely available through some websites, including Thingiverse and GrabCAD, and the advantages of these geometries are portability and scalability. These free geometries make the adoption of the technology more accessible.

An additional benefit in the use of 3DP is found in this research. Unlike previous research using high fidelity replicas in support of teaching, this research contributes to exploring alternative and innovative learning applications using an enlarged, single-color 3DP insect prototype created with low-cost 3D printers. The role of 3DP in natural sciences learning has yet to be fully explored. Some potentially important factors could impact learning. For example, one of the learners exhibited a pronounced fear of insects which caused her considerable anxiety at the beginning of the activity. The instructor's patient and repeated explanation that the models were not actual insects gradually helped her overcome this fear and she eventually actively participated. A possible study could be to investigate the impact on those children who might find insects frightening; a definite replica model might encourage those learners to handle as well as closely observe the insect models.

Furthermore, previous studies have shown that incorporating mobile and gamification technologies into biological learning processes could produce better learning outcomes [46], such as the development of virtual butterfly ecological systems [47]. Future research could incorporate the use of the 3DP insect prototype learning kit with ICT related applications, such as the use of AR in mobile devices [48] or VR for insect living environments [49].

4.3. Further Exploration on Digital Media-Based 3DP Application in Learning

Despite the fact that the current study made important observations in regard to the design and support of a novel learning aid through the insect prototype, this study unavoidably has limitations. The results of the research study are applicable to a small number of pupils at the chosen school. They cannot be generalized to the entire population of fourth graders. Furthermore, the experiment only lasted for a short time. Only students' short-term memory was tested. To what extent this study may have impacted their long-term memory is as yet unknown. Moreover, the 3DP insect prototypes also produced an unexpected learning effect due to the enlarged single-color prototype that did not reflect the real-life insect. In this study, we only used two colors, yellow and white, due to technical constraints, for the insect prototypes that did not completely mimic the color of the real insects.

Future improvements in the 3DP insect prototype include the material and assembly aspects. The solid insect prototypes and their component puzzles were not as robust as they could have been due to the 3DP material characteristics and printing process. Different materials could be used to produce a more durable learning kit. Additionally, possible improvements in modifying 3D models (particularly in intersection parts and joints in making 3DP insect prototypes) would be helpful in reducing 3D printers' printing time and failure rates.

5. Conclusions

This study used digital media—in this case, 3D printing technology—to create 3D prototypes and assemble components for elementary school instruction of insect sections and parts, and found that the learning performance was best for the group using the insect prototype compared to the photo card group and the group that used traditional learning aids. Our results offer important support for the innovative and sustainable use of digital media in 3DP for teaching and learning about insects, especially for those pupils in city schools that are presented with the challenges of not easily acquiring real life insects. The implications of this study are twofold. First, given the availability of the technology, the

3D prototypes can be effective aids for city learners. Second, photos of the 3D prototypes have some benefits. The availability of the 3D prototypes depends on the equipment and technical skills of teachers or other school staff to make the prototype. Photos of the 3D prototypes are relatively easy to produce; however, they are less effective. Furthermore, this study went through a careful design process to develop the innovative pedagogical aids, which may provide a useful point of reference for both researchers and practitioners who are interested in exploring innovative and sustainable learning. Future work should expand on this work using a wider range of domain-specific learning content and different evaluation metrics.

Author Contributions: S.-J.L. and Y.-C.L. developed the concept and data audit of this study, and made a significant contribution to the analysis checking, manuscript writing, and final manuscript revision. Y.-H.C. made the test and performed data collection and data analysis. H.H. supported our data collection, analysis, and administration. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Introductory teaching materials were developed for the two experimental groups, and the control group used the e-book. The instruction manuals, presented in a PowerPoint file format with 18 pages, were used by the instructor to brief them. Slide content was mostly text and images. The first three slides presented background information, e.g., the course unit, a review of prior knowledge, and the introduction of upcoming learning activities. The fourth and sixth slides reminded learners to observe and draw each insect from above and on the belly side.

The seventh slide prompted learners to guess the insect anatomy before the instructor provided the correct answers. The learning content was demonstrated in a visual representation from above and below each observed insect, and each learner was asked to label the various parts of the insects using the vocabulary items shown in the slide (e.g., head, thorax, abdomen, antenna, wings, legs, etc.). The eighth slide was used for the group using only the 3D prototypes and aimed to guide the learner to physically manipulate the individual 3D-printed insect components to produce a complete insect. This slide presents the labeled components for assembly into a completed insect.

The 9th to 14th slides provided answers for the correct assembly of the insect models and were to be used following the learning activities. The answers to the questions are provided in both the top and bottom view, with each component labeled. The instructor could use these slides to prompt learners to verify their previous answers. Slides 15 and 16 summarized the learning content and could be used to integrate and review the main concepts, including basic insect physiology. Slide 17 presented a simple classroom quiz while Slide 18 presented statements to encourage learners to continue investigating other insects.

Appendix B

Part 1: The ARCS learning motivation scale.

Item	Question
Attention (ATTEN)	
ATTEN1	The teaching method of this course is interesting and attractive to me.
ATTEN2	The content of this course will be/were interesting throughout.
ATTEN2	The way this course is explained helps me focus
ATTEN3	The content of this course is not clear and specific enough, making it difficult for me to concentrate
ATTEN4	The way the course content is presented in the teaching aids helps me focus
ATTEN5	I am deeply impressed by the teaching aids in this course.
ATTEN6	The presentation of the teaching aids in this course, the method of explanation, and the various exercises can help me concentrate.
Relevance (REV)	
REV1	From the introduction in the first part of the class, I will know what I will learn/knew what I would learn about in the remainder of the course.
REV2	The content of this course is relevant to the knowledge I have learned before.
REV3	It is very important for me to study the content of this course.
REV4	This course is related to or in line with my usual interest.
REV5	I will know/know how to apply what I will learn/learned in the course.
REV6	I will learn/learned something from this course that I didn't expect to learn.
REV7	I can connect the content of this course with things I have learned or done and thought about before.
Confidence (COF)	
COF1	The content of this course is just right for me, neither too difficult nor too easy.
COF2	When I am studying this course, I am confident that I can learn it well.
COF3	This course will be/was too difficult for me.
COF4	There are a lot of repetitive parts in this course that make me feel very tired.
COF5	After studying this course, I think I can answer the exam questions related to the course.
COF6	I don't think I need to take this course because I already know its content.
COF7	Because the content of this course is very organized, I have the confidence to learn it well.
Satisfaction (SAT)	
SAT1	After learning all the content of this course, I will feel/felt very rewarded.
SAT2	I like this course very much, and I hope to have the opportunity to learn more about it.
SAT3	I will enjoy/enjoyed this course very much.
SAT4	The content of this course and the way it is explained make me feel that it is worth learning.
SAT5	In this course, the teacher can give me positive encouragement in a timely manner.
SAT6	After finishing this course, I feel/felt very fulfilled.
SAT7	I am very happy to have the opportunity to study this course.

Part 2: Open-ended question.

1. What do children think the most fun part of this course? Please describe it in words.
2. What new things do you think to be more interesting for the children? Please describe it in words.

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