The Genetics Conceptual Understanding of Indonesian and United States Undergraduate Biology Students

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Abstract

Genetics as a core concept of life science is essential for understanding biology. Examining genetics understanding among biology majors is becoming important since they must necessarily achieve some level of genetics understanding to advance their career. This study compares Indonesian biology majors’ genetics understanding with previously published data from students in the United States (US). This study also identifies the effect of academic year and program on genetics understanding.
by administering the Genetics Concept Assessment (GCA) to 377 biology majors in Indonesia. IRT-Rasch modeling was performed for instrument validation, followed by one-way ANOVA and independent sample t-test for the analysis. The results showed that Indonesian biology majors' genetics understanding was significantly affected by academic year but was not affected by the academic program. Indonesian biology majors had a slightly similar level of genetics understanding with US non-majors' pre-test scores, while Indonesian biology majors' scores were two times lower than US majors' post-test scores. The implications of reducing the gap between two countries are discussed.

Keywords

biology majors – conceptual understanding – genetics – Indonesian students

1 Introduction

These days, with the support of the advancement of science and technology, genetics has grown rapidly and offers many advantages for human life. As a discipline of biology, the core theories of genetics make it unique and enable the provision of rough solutions and explanations for many problems, including biological problems (Sager & Ryan, 1963). For instance, genetics identifies the particular genes containing a risk of a specific disease inherited by offspring. With genetics information, scientists can produce drugs or suggest treatments to prevent the disease early on. Thus, genetics information allows humans to diagnose, prevent, and treat hazardous diseases related to their genetics. In other cases, genetics can identify people's biological parents or children and even help police to catch criminals. Considering the formidable role of genetics in daily life, genetics is becoming a central topic of interest for various fields of study.

As one of the core concepts in biological sciences, the understanding of genetics is essential for understanding biology itself, and even understanding concepts of genetics is a critical aspect of scientific literacy (AAAS, 1993; Cary & Branchaw, 2017). However, improving the understanding of genetics requires greater attention in the educational system since this domain is not trivial to understand (Duncan & Reiser, 2007). Students and teachers often perceive that genetics is a difficult concept to be learned (Duncan & Reiser, 2007; Gericke & Hagberg, 2007) and taught (Gericke & Wahlberg, 2013;
Lewis & Kattmann, 2004), even for biology majors (Coley & Tanner, 2015; Marbach-Ad & Stavy, 2000).

Despite the challenges in learning genetics, its use in international comparative tests has been considerable. To evaluate a country's position internationally, standardized international testing programs (e.g., PISA and TIMSS) have been conducted. The results of PISA and TIMSS can help educational stakeholders reflect on the success of their endeavors in science education and enable them to consider the ways to improve the quality of learning in science (Carter, 2005; DeBoer, 2011). While the PISA and TIMSS results compare high school students' performance in mathematics and science, there has still been a lack of international comparative study of undergraduate students' performance in science. Conducting cross-national research on undergraduate performance is also important since it can indicate students' readiness in preparing for careers after graduation.

In this study, we intended to examine the genetics understanding among biology majors from the megadiverse country of Indonesia. As genetics is a core life science concept, examining learning progressions of genetics concepts is essential to providing teachers with a framework to evaluate students' levels of understanding. The framework can be used to describe the path that students might take in moving from novice to expert understanding in learning genetics. By knowing students' learning progressions, teachers may guide students towards a more sophisticated level of understanding through the systematic and successful teaching of core concepts (Alonzo & Steedle, 2009; Neuman, Viering, Boone, & Fischer, 2013). Therefore, this study examines the Indonesian biology students' genetics conceptual understanding across academic years. We also consider that even though they are biology students, some will focus on being teachers (biology education) and others will focus on being scientists (biology science), so their academic program may result a difference in students' levels of genetics understanding. Thus, we examined the effect of academic program as well.

Even though Indonesia is still developing in scientific advancement, as one of the megadiverse countries, Indonesia is a plentiful source of genetic diversity and scientific study of this diversity through genetics could greatly contribute to our understanding of genetics in the future. However, this will require that Indonesian universities and research centers be able to produce students with advanced genetics understanding. To understand the current circumstance of genetics education in higher education, we examined Indonesian undergraduate biology students' performance on genetics to compare to other countries. For this study, we decided to use data from a country with documented
success in genetics education. For this reason, we selected the United States as a comparative measure. The United States is a pioneer country in research in genetics, having had more than 100 researchers who earned Nobel prizes for their work in this field (Ferreira et al., 2017). Also, based on web tracking trends and performance in basic research (see sciencewatch.com) from Thomson Scientific essential science indicators, the United States is always in the top three countries for relative impact of molecular biology and genetics research, making it one of the most competitive countries for studying genetics. The outstanding development of genetics research and education in the United States can be a benchmark to reflect the quality of Indonesian genetics education on the global scale. As Indonesia also shares similarities with the United States in terms of ethnic and cultural diversity, it is interesting to compare the genetics education of both countries (Bazzi, Gaduh, Rothernberg, & Wong, 2017).

In this paper, we share findings from a comparative study examining genetics understanding among undergraduate students from both countries. Based on this comparison, we identified several differences in genetics education. Next, we share findings taken from several items on the Genetics Concept Assessment (GCA) (Smith, Wood, & Knight, 2008), which showed a large gap in the genetics understanding of students from Indonesia and the United States. Building from these findings, we offer valuable insights for improving particular aspects that might be still lacking in Indonesian science curriculum in genetics.

Based on this background, the following three research questions were proposed as the focus of this study:

1. What is the level of genetics understanding of Indonesian biology majors across academic years and programs?
2. What is the level of genetics understanding of Indonesian biology majors compared to those in the United States?
3. What factors may impact on Indonesian and US students’ relative performance on genetic concept assessment (GCA) items?

2 Literature Review

2.1 Review of Genetics Education in Indonesia and United States

In Indonesia, genetics is taught as part of formal education and is included in the science curriculum arranged by the Indonesian government. Our review of the Indonesia science curriculum specifically in the genetic concepts for elementary, middle, and high school was based on data accessed from the official website of the Indonesia Ministry of Education and Culture (http://kurikulum.kemdikbud.go.id/) referred to the latest Indonesian curriculum
called Kurikulum 2013 (Kemendikbud, 2013). The students begin to learn genetics in the last grade of middle school, which is the ninth grade. They learn about genetic materials, such as DNA and RNA, and about biological inheritance. After that, genetics is included in the high school and vocational school curriculum. In high school, genetics is taught to 12th-grade students in the science track. Some lessons are quite similar to what is taught in middle school, yet high school students learn more complex topics, such as genetic variation and manipulation. In vocational school, genetics is only taught to students who enroll in particular tracks such as nursing, pharmacy, agriculture, and forestry.

When students enter the university, genetics is taught in certain majors, including biology. There are two kinds of academic programs for biology majors in Indonesia: biology science and biology education. Biology science is for students preparing to be biologists or researchers in a specific branch of biology, such as zoology and microbiology. Meanwhile, biology education is for students preparing to be biology teachers for students in middle school science or in high school biology courses. In Indonesia, some universities, especially education-based universities, provide both programs for biology majors. However, general universities only provide the biology science program. The current study investigates Indonesian biology majors in a university that has both biology science and biology education programs. The genetics curriculum review for undergraduate students is drawn from the official website of biology majors in the Universitas Pendidikan Indonesia (http://biologi.upi.edu/v2/) referred to the 2016 Curriculum (UPI, 2016).

The biology education and biology science programs have different curriculums. Biology science students take the genetics course in the first semester of the third year, but biology education students enroll in a genetics course in the second semester of the third year. However, before entering a genetics course, all students will have studied some genetics concepts through related courses, such as general biology, biochemistry, and cell biology. For example, in general biology, first-year students learn genetics concepts that are similar in scope to what they learned in high school but in more detail, such as Mendelian genetics. Second-year students learn genetics in more comprehensive courses, such as biochemistry and cell biology, where they learn the concepts of cell division (mitosis and meiosis), biological processes (e.g., replication, restriction, recombination, etc.), and protein synthesis. Third-year students take genetics as a core course. In the genetics course, students have lecture class, which typically consists of genetics concepts being explained by the lecturer and they have a laboratory class where students conduct some group activities (such as calculating the basic probability and Chi-squared test in Mendelian genetics). Here, the students learn more in-depth genetics concepts such as the
molecular anatomy of DNA, gene expression, mutation, and population genetics. Further, in the fourth year, biology science students learn about genetics in other related courses such as plant development, evolution, biotechnology, and molecular biology. However, biology education students only take plant development, evolution, and biotechnology courses. A review of this curriculum showed that Indonesian biology majors learn genetics concepts in each year through genetics courses or genetics-related courses.

In the United States, according to the framework for K-12 science education (NRC, 2012), heredity is studied as one of the four core concepts of life science along with molecules to organisms, ecosystem, and biological evolution. This core concept focuses on the flow of genetic information and consists of two components: inheritance of traits and variation of traits. The students begin to learn genetics in elementary school. Second-grade elementary students are taught the concept of similarities and differences within living organisms (e.g., plant and animal), and fifth-grade students learn about the specific characteristics that are inherited from the parents and how the environment affects those characteristics in growing individuals. At the middle school level, eighth-grade students learn about genes, chromosomes, mutations, and the mechanism of genetic inheritance between generations. In high school, 12th-grade students learn more in-depth genetics topics, such as gene expression and its alteration, and the impact of the environment on gene expression and its probability of occurrences in the population.

At the university level, genetics is taught to science and non-science major students. At the University of Colorado-Boulder, whose students’ data were used in this study, both major and non-major undergraduate students take a genetics course (Smith & Knight, 2012). The genetics courses for both non-majors and majors share some materials and learning goals, including information about genes, alleles, and gene functions; the molecular anatomy of genes, genomes, and the mechanism of genomes passing to the next generation; mutation; and molecular analyses used to determine inheritance patterns and causes of mutation. For biology majors, genetics is a core course in the department of molecular, cellular, and developmental biology (MCDB). Students complete an introductory MCDB course that includes basic knowledge of cell and molecular biology before enrolling in a genetics course. Their genetics class consists of a weekly laboratory and lecture with an active-learning approach. In active learning, lecturing is interspersed with questions that must be answered by students using a clicker. The class discusses the answers to clicker questions in which students are encouraged to talk to each other and do group problem-solving. The genetics laboratory course consists of genetics experiment activities, but is taught by a different lecturer and covers different
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materials from the lecture class. Meanwhile, for non-science majors, genetics can be taken to fulfill part of the science distribution requirement. The genetics class for non-majors consists only of lecture with an active-learning approach (Knight & Smith, 2010).

2.2 Prior Studies about Genetics Instruction for Indonesian and US Biology Majors

Although there have been a limited number of studies published in international journals regarding the level of genetics understanding among Indonesian biology majors, some local studies have been conducted on this topic (Darmawati, Amelia, & Srifatmini, 2011; Hariyadi, 2015; Mustika, Hala, & Arsal, 2014; Nusantari, 2012); however, these have been more focused on students’ misconceptions and how genetics instruction is implemented. Those studies have found that Indonesian biology majors have misconceptions in some genetics topics such as basic concepts in genetics (genes, DNA, and chromosomes), mechanisms of inheritance, protein syntheses, reproduction and expression of genetic materials, and mutation (Mustika et al., 2014; Nusantari, 2012). Those studies have also suggested that one of the factors causing students’ misconceptions is errors in the textbooks. Beyond the misconception issue, Darmawati et al. (2011) suggested that Indonesian undergraduate students tend to be passive and less opinionated and struggle with solving the mathematical calculations in genetics instruction.

As opposed to Indonesia, many studies about genetics understanding among US undergraduate students have been published in international journals, along with research about the development of genetics assessments, such as the Test of Basic Genetics Concepts [TBGC] (Sadler & Zeidler, 2005), the Genetics Concept Assessment [GCA] (Smith et al., 2008), the Molecular Biology Capstone Assessment [MBCA] (Couch, Wood, & Knight, 2015), the Learning Progression-based Assessment of Modern Genetics [LPA-MG] (Todd & Romine, 2016), and the Genetic Drift Inventory [GDI] (Price et al., 2014). In addition to studies of genetics concept inventories, there has been some research about genetic misconceptions among undergraduate students (Andrews et al., 2012; Wright, Fisk, & Newman, 2017).

3 Methodology

3.1 Participants

The data were collected from Indonesian undergraduate biology majors in two academic programs at a university-based education: biology education
and biology science. There were 377 participants in this study, consisting of 247 biology education students and 130 biology science students. Of these 377 participants, 86 (23%), 114 (30%), 106 (27%), and 71 (18%) were first-, second-, third-, and fourth-year students, respectively. In the present study, biology science students took the genetics course in the first semester of the third year, while biology education students enrolled in a genetics course in the second semester of the third year. They not only learned genetics concepts from a genetics course, but also from other genetics-related courses. Previously published data from the United States were used as a comparison in which data was taken from undergraduate students (Smith & Knight, 2012) consisting of 751 participants, with 630 major students and 121 non-major students.

3.2 Research Instrument and Validation

To assess the undergraduate students’ genetic understanding, we used the GCA, which was designed, developed, and validated by Smith et al. (2008). The instrument consists of 25 multiple-choice questions and is designed to be concise and as free of jargon as possible. Smith et al. (2008) added that the questions were aimed at assessing students’ conceptual understanding of genetics rather than simple factual recall. Each question was specifically designed to cover one or more of nine topics: (1) phenotypic data and pattern of inheritance from family histories; (2) molecular anatomy of genes and genomes; (3) mechanism by which an organism’s genome is passed on to the next generation; (4) phenomenon of linkage and how it affects assortment of alleles during meiosis; (5) genes, alleles, and gene functions; (6) the process that can affect the frequency of phenotypes in a population over time; (7) different types of mutations and how each can affect genes and the corresponding mRNAs and proteins; (8) the application of the results of molecular genetic studies in model organisms to understanding aspects of human genetics and genetic diseases; and (9) the interpretation of the results from molecular analyses to determine the inheritance patterns and identities of human genes that can mutate to cause disease. This instrument has been widely used to assess students’ understanding of genetics, even in non-English speaking countries (Agorram, Zaki, Selmaoui, & Khzami, 2017; Marcos-Merino, Gallego, & de Alda, 2019). In this study, we asked experts to translate 25 questions of the GCA into Indonesian-Bahasa. An example item is presented in Table 1.

Regarding the instrument validation, the instrument developer (Smith et al., 2008) has validated the GCA using the classical test theory (CTT). In this study, since we translated the GCA into Indonesian-Bahasa, we re-validated the GCA through item response theory (IRT)-based Rasch modeling. IRT-Rasch analysis provides more robust evidence for validity, including item quality
The Rasch fit properties of the Genetics Concept Assessment (GCA) instrument are shown in Table 2. The values of infit and outfit MNSQ were both in the range of 0.8–1.40 (Boone, Staver, & Yale, 2013), indicating that all GCA items were well-fitted with the Rasch modeling. The results of Rasch analysis also showed that the item reliability of this instrument was 0.97 (high reliability), indicating that the instrument was reliable to investigate the genetics understanding of undergraduate students.

### Table 1: An example of Genetics Concept Assessment (GCA) item

| No | Item | Genetics Concept Assessment (GCA) v.6.22 No 1 |
|----|------|---------------------------------------------|
|    |      | Which of the following human cells contains a gene that specifies eye color? |
| a) | Cells in the eye |
| b) | Cells in the heart |
| c) | Gametes (sperm and egg) |
| d) | Cell is the eye and gametes |
| e) | All of the above |

### Table 2: The Rasch fit properties of the Genetics Concept Assessment (GCA)

| Item | Measure | Infit MNSQ | Outfit MNSQ | Item | Measure | Infit MNSQ | Outfit MNSQ |
|------|---------|------------|-------------|------|---------|------------|-------------|
| GCA1 | 0.89    | 0.96       | 0.89        | GCA14| −0.74   | 1.01       | 1.00        |
| GCA2 | −1.36   | 0.98       | 0.98        | GCA15| −0.05   | 1.00       | 1.01        |
| GCA3 | −0.34   | 1.00       | 0.99        | GCA16| 0.17    | 1.04       | 1.09        |
| GCA4 | −0.35   | 1.02       | 1.02        | GCA17| −0.18   | 0.96       | 0.94        |
| GCA5 | 2.43    | 1.02       | 1.25        | GCA18| −0.36   | 1.02       | 1.02        |
| GCA6 | 0.23    | 0.99       | 0.98        | GCA19| −0.49   | 1.00       | 1.00        |
| GCA7 | −0.51   | 0.98       | 0.97        | GCA20| −0.45   | 1.00       | 1.00        |
| GCA8 | −0.78   | 1.01       | 1.02        | GCA21| −0.27   | 1.03       | 1.05        |
| GCA9 | 0.51    | 1.01       | 1.01        | GCA22| −0.11   | 1.01       | 1.00        |
| GCA10| 0.98    | 1.02       | 1.07        | GCA23| 0.37    | 0.99       | 0.97        |
| GCA11| 0.06    | 0.96       | 0.93        | GCA24| 0.82    | 1.00       | 1.01        |
| GCA12| −0.05   | 1.02       | 1.02        | GCA25| −0.07   | 1.00       | 0.99        |
| GCA13| −0.35   | 0.98       | 1.00        |
3.3 Data Analyses

To address the first research question, a one-way ANOVA test was performed to determine the effect of the academic year on the conceptual understanding of genetics of Indonesian biology majors. The analysis was continued using Tukey’s post hoc test to identify how the specific groups differed. Further, an independent sample t-test was conducted to determine whether there were any significant differences in genetics understanding between the two academic programs of biology science and biology education. With respect to the second research question, the average GCA scores of Indonesian biology science and biology education majors were compared to those of US major and non-major students (Smith & Knight, 2012). Smith and Knight’s (2012) study provided the percentage correct on each question of combined data from all 751 students (630 major and 121 non-major students). We also calculated the percentage correct on each question of all 377 Indonesian students’ data. Therefore, to address the third research question, the gap between Indonesian and US students’ was calculated by subtracting the percentage correct on each question.

4 Result and Discussion

4.1 Genetics Understanding of Indonesian Biology Majors across Academic Years and Programs

In the current study, the genetics conceptual understanding was represented by GCA score in the form of person measure. This quantitative measure is ratio-scaled scores of each person on genetics produced by Rasch model with the logit as its unit. The person measure represents a more accurate score inference and comparison between item and person (Boone et al., 2013). The comparison of GCA score among four academic years is presented in Figure 1. As shown in Figure 1a, the current study found that the average GCA score of fourth-year students (M = −0.85, SD = 0.49) was the highest, followed by third-year students (M = −0.97, SD = 0.45), first-year students (M = −1.11, SD = 0.49), and second-year students (M = −1.06, SD = 0.50). The results of the ANOVA test showed that the academic year significantly affects students’ conceptual understanding of genetics (F[3, 376] = 5.11, p = .002, PES = 0.039). Further analysis was conducted in order to determine which academic year was significantly different from the others through Tukey post hoc tests. The current study found that the first- and second-year students differed significantly in terms of their levels of genetics conceptual understanding from fourth-year students (p-values are .026 and .002, respectively), while the third-year students did not significantly differ from the first-, second-, or fourth-year students (p-values > .05). This indicates
that the conceptual understanding of genetics among Indonesian biology majors increases as the academic year progresses.

Based on these results, it was found that the genetics conceptual understanding is influenced by the student's academic year, which can be expected as generally, students who are in higher academic years have better genetics understanding. In this study, the fourth-year students had significantly higher GCA scores than the other three academic years. It might be caused by the gradual effect of learning genetics concepts through other courses before enrolling in a genetics course in the third year. Similarly, the study by Schmiemann, Nehm, and Tornabene (2017) also found that the number of relevant courses completed was correlated with genetics performance. According to the curriculum analysis of Indonesian biology majors, there are some courses related to genetics that are administered to students before they enroll in a genetics course in the third year, such as general biology in the first year and biochemistry and cell biology in the second year. When taking those courses, Indonesian biology majors learn some content that corresponds to the GCA items such as inheritance and its patterns, cell division, and DNA recombination. Therefore, those courses help students become familiar with genetics concepts and with terms used in genetics problem types. Indeed, being familiar with genetics terms or problems could be expected to help the students to perform better (Clough & Driver, 1986; Schmiemann et al., 2017; Ware & Gelman, 2014). Next, when students enrol in genetics as a core course, they learn about the molecular anatomy of DNA substances (corresponding to the fifth point of GCA content), gene expression (correspond to the ninth point of GCA content), mutation (correspond to the seventh point of GCA content), and population genetics.
(correspond to the sixth point of GCA content). The content in the genetics course is indeed developing students’ genetics understanding. These results confirmed the learning progression of genetics across multiple academic years, suggesting that the genetics curriculum of Indonesian biology majors, particularly the order or sequencing of the genetics-related courses, provides students with the opportunity to gradually develop a deeper understanding of genetics (Stevens, Delgado, & Krajcik, 2010). This means that the course arrangement has guided students’ progression from the lowest level of genetics understanding towards the most advanced level (Neumann et al., 2013).

Further, the comparison of GCA score between the two programs – biology education and biology science – is also visualized in Figure 1. As shown in the Figure 1b, the biology science students (\(M = -1.00, SD = 0.51\)) had a relatively higher mean than those in the biology education program (\(M = -1.01, SD = 0.48\)), even though it was not statistically significant (\(t = -0.12, df = 375, p = .902, d = 0.01\)). Even though biology science students have more in-depth courses related to biological content than biology education students, their performance on genetics is higher, but not significantly different. This may be because the same faculty who teach the courses for biological content (including genetics course) in the biology science program also tend to teach in the biology education program. Further, the learning goals and teaching materials may be similar. As a result, no significant difference in genetics understanding between biology science and biology education students was produced.

### 4.2 Comparison of Genetics Understanding between Indonesian and US Biology Majors

A comparison of genetics understanding between Indonesian biology majors and previously published US data is presented in Figure 2. The GCA mean scores of Indonesian students in biology education and biology science majors and even the overall mean score were relatively similar to the US non-major students before taking a genetics course (pre-test). The overall Indonesian performance on the GCA showed a mean score of about 30 out of 100. However, the US students’ average score was more than 30, even for those students who had not yet enrolled in genetics courses and for those who were not even majoring in biology.

The current study of a cross-national comparison of genetics understanding found that US students achieved better GCA scores than Indonesian students overall. Further, the combined GCA mean score of Indonesian students both majoring in biology education and biology science was approximately similar to that of US non-major students before they started taking genetics courses (pre-test). This outcome may be due to the differences in the genetics curriculum or the approaches to genetics teaching and learning between the two countries.
In terms of the genetics curriculum, before going to the university, Indonesian students learned genetics in middle and high schools, while US students are introduced to genetics concepts from the elementary school level. In this case, the genetics curriculum of each country sets a different time frame for learning about genetics concepts. According to Knight and Smith (2010), the length of the study has an impact on performance which could potentially have yielded the observed differences in genetics understanding between Indonesian and US students.

The different approaches in teaching and learning genetics can also be an aspect affecting the GCA scores of those countries. For Indonesian biology majors, lecturing is the most common method of genetics instruction (Darmawati et al., 2011; Hariyadi, 2015; Suratsih, Henuhili, Rahayu, & Hidayat, 2009). Additionally, according to Primandiri and Santoso (2015) and Suratsih et al. (2009), genetics instruction for biology majors is textbook oriented where the textbook is usually written by faculty members. Primandiri and Santoso (2015) added that genetics textbooks are often out of date and dominated
by classical genetics concepts, while there are more items in the GCA instrument related to molecular genetics concepts than to classical genetics (Smith et al., 2008). In the United States, besides lecturing, incorporating active learning into genetics instruction was implemented for the students in this study (Smith & Wood, 2016). Active learning allows undergraduate students to practice genetics problem-solving in class, with the lecturers monitoring their learning process. Therefore, the students were trained to be familiar with genetics problem-solving rather than receiving passive learning involving only listening to lecturers’ explanations.

The lower genetics understanding among biology education students as prospective teachers is likely to result in passing on misconceptions to students in the future. Since having a certain level of genetics understanding is a crucial aspect of being scientifically literate (Todd, Romine, & Cook Whitt, 2017), if this condition continues to occur, the goal of the Indonesian science curriculum will not be achieved, given that the main goal is to increase the students’ scientific literacy achievement in the international assessments. Therefore, it is not likely to increase Indonesian students’ performance in international assessments of students’ scientific literacy, such as PISA and TIMSS. In addition, the genetics misconceptions that teachers pass on to their students can be an obstacle to achieving learning goals in school. With respect to biology science students as prospective biology scientists, having a low level of conceptual understanding will not allow them to become creative researchers who can generate novel ideas. To tackle this issue, genetics instruction among biology majors should be tailored so that students can meet the required level of understanding. Supplementing or replacing the conventional lecturing with active learning strategies can be an alternative that can encourage the students’ motivation in learning genetics and help them to master genetics concepts, even difficult ones (Smith & Wood, 2016).

4.3 The Item Analysis of the Genetics Concept Assessment (GCA)

Some of the 25 GCA items delivered to undergraduate students showed a large gap between Indonesian and US scores. In this study, the six items with the biggest gap were Items 1 and 13 (topic: analyze the phenotypic data to find the pattern of inheritance), Items 5 and 6 (topic: types of mutations and their effect on genes), Item 16 (topic: mechanism of how a genome passed on to next generation), and Item 19 (topic: interpret the results of molecular analysis to determine the inheritance pattern of mutating diseases; Smith et al., 2008).

Table 3 shows that the biggest gap in scores occurred in Item 5 (47%), followed by Items 1 (46%), 19 (43%), and 13 (38%). Items 6 and 16 showed gaps
**TABLE 3** The top six items of GCA generating the biggest gap between Indonesian and US students’ score

| Item  | Questions                                                                 | % of each option selected among Indonesians | % correct of Americans (Smith & Knight, 2012) | % gap   |
|-------|---------------------------------------------------------------------------|--------------------------------------------|----------------------------------------------|---------|
| GCA 1 | Which of the following human cells contains a gene that specifies eye color? | a) 16.1%                                   | 59.8%                                        | 45.9%   |
|       | a) Cells in the eye                                                       | b) 0%                                      | 0%                                           |         |
|       | b) Cells in the heart                                                     | c) 26.6%                                   |                                              |         |
|       | c) Gametes (sperm and egg)                                                | d) 43.4%                                   |                                              |         |
|       | d) Cells in the eye and gametes                                           | NA 0%                                      |                                              |         |
|       | e) All of the above*                                                      |                                            |                                              |         |
| GCA 5 | An isolated population of prairie dogs has longer than average teeth. As a result, they can eat more grass with less effort and are better able to survive. The mutation(s) that resulted in longer teeth: | a) 15.5%                                   | 50.5%                                        | 47.1%   |
|       | a) Allowed the teeth to grow longer over several generations until they reached an optimal length for eating grass | b) 6.1%                                   |                                              |         |
|       | b) Arose in many members of the population at the same time               | d) 51.3%                                   |                                              |         |
|       | c) Happened by chance*                                                    | e) 23.4%                                   |                                              |         |
|       | d) Occurred because the prairie dogs needed to be more efficient at eating grass to survive and reproduce | C 3.4%                                     |                                              |         |
|       | e) Would only occur in a prairie dog population that eats grass and would not occur in a population that lives on seeds | NA 0.3%                                    |                                              |         |
### Table 3
The top six items of GCA generating the biggest gap (cont.)

| Item | Questions                                                                                                                                                                                                 | % of each option selected among Indonesians | % correct of Americans (Smith & Knight, 2012) | % gap (rounded to 35%) |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------|-----------------------------------------------|------------------------|
| GCA 6 | Starting with a population of genetically identical mice, you discover two new independent mutant strains in which all of the animals have epileptic seizures. In both strains, you know that the epileptic seizures are due to a single DNA mutation. You cross a mutant mouse from one strain to a mutant mouse from the second strain and find that none of their many offspring undergo spontaneous seizures. From this experiment you would conclude that the two mutant strains of mice most likely have mutations in:  
   a) The same DNA base position within a particular gene  
   b) The same gene, but not necessarily the same DNA base position.  
   c) Two different genes* | a) 19.2%  
b) 55.5%  
C 23.2%  
NA 2.1% | 58% | 34.8% |
A man is a carrier for Wilson’s disease (Aa) and Rotor syndrome (Rr). Assume the genes involved in these two disorders are both on chromosome 13 (a non-sex chromosome). Below are possible representations of his genotype (labeled #1, #2, and #3). Which of them could be correct?

- a) #1 only
- b) #2 only
- c) #3 only
- d) #2 and #3 only*
- e) #1, #2, and #3
| Item   | Questions                                                                 | % of each option selected among Indonesians | % correct of Americans (Smith & Knight, 2012) | % gap          |
|--------|---------------------------------------------------------------------------|---------------------------------------------|-----------------------------------------------|----------------|
| GCA 16 | Below is a pedigree of a family in which all the people in generation II are dead (indicated with a slash) because of political unrest in their country. Circles represent females, squares represent males. Which children in generation III could be traced to the grandmother in this pedigree by using only mitochondrial DNA sequences: a) A and D b) A, B, and C* c) B, C, and E d) A, B, C, D, and E | a) 18.9%                                    | 59%                                           | 34.5% (rounded to 35%) |
|        |                                                                           | c) 32.4%                                    |                                               |                |
|        |                                                                           | d) 21.1%                                    |                                               |                |
|        |                                                                           | C  24.5%                                    |                                               |                |
|        |                                                                           | NA  3.2%                                    |                                               |                |
Polydactyly is an inherited trait that results in extra fingers or toes. In the United States, 0.1% of the population exhibits polydactyly. People with polydactyly have the genotype Pp, where P represents the allele that causes polydactyly and represents the normal allele of this gene. Which of the following is true?

a) The P allele is more frequent in the US than the p allele
b) The P allele is less frequent in the US than the p allele*
c) The two alleles, P and p, are at approximately equal frequencies in the US population
d) There is not enough information to answer this question

Notes. * = the correct answer, C = percentage of the correct answer, NA = percentage of no answer of 35% between the Indonesian and US scores. Large differences in scores between Indonesian and US students may be caused by several factors, such as the item difficulty and low genetics understanding among Indonesian students. The difficulty in answering questions might be due to the distractor options. Thus, we analyzed the most chosen distractor of each item (Table 3).

For Item 5, most Indonesian students chose D (distractor) 15 times more than C (correct answer). D was the most chosen distractor in Item 1, as it was selected three times more than the correct answer, E. In Items 13 and 19, most students answered the correct answer (D and B, respectively), yet the second-most chosen option in both items was A, which was the item distractor. For the Item 16, option C (distractor) was chosen 8% more often than the correct
answer (B). Last, in Item 6, students chose the distractor (B) two times more than C (correct answer).

According to Smith and Knight (2012), US undergraduate students considered Item 1 “Which of the following human cells contains a gene that specifies eye color?” one of the most challenging questions in the GCA. As shown in the results, this item showed the second biggest gap between the Indonesian and US scores, which indicates that the low scores of Indonesian students in this item are likely due to item difficulty. Table 3 shows that Indonesian students were more likely to choose D, “cells in the eye and gametes,” than E as the correct answer, which also occurred with US students in the study conducted by Smith and Knight (2012). Students tended to think that different cells in the human body contain different genes and provide specific responses such as “only genes in the eye contribute to eye things”. However this is wrong. While each cell type in the human body contains essentially the same gene, the gene for eye color is also present in the eye, heart, and gametes cells – even though it is only in the eyes that the gene is expressed for specifying eye color (Reece et al., 2010).

In the other items (Items 5, 6, 13, 16, and 19), the US students considered these items easy questions, indicating that only Indonesian students experienced difficulty in answering those items. In Item 5, “An isolated population of prairie dogs has longer than average teeth. As a result, they can eat more grass with less effort and are better able to survive. The mutation(s) that resulted in longer teeth...,” the distractor D also successfully deceived the students. Instead of choosing the correct option about mutations happening by chance (C), the students chose the option suggesting that mutation resulted in the longer teeth of prairie dogs due to an adaptation for efficiency in eating grass (D). According to Lodish et al. (2000), the mutation occurs randomly and spontaneously in DNA sequences during DNA replication, resulting in a change in DNA structure. Whether or not a particular mutation happens is unrelated to how useful the mutation is. Thus, the mutation occurred spontaneously to prairie dogs’ teeth and was not related to its function for eating grass. This case corresponds with several Indonesian studies (Mustika et al., 2014; Nusantari, 2012) that have suggested that the mutation concept was the third most robust misconception in genetics among Indonesian students. Nusantari (2012) found that students were likely to think that mutation aims for gene conservation. Most students believe that mutation occurs for particular goals rather than occurring randomly.

Similar to Item 5, in Item 6, “Starting with a population of genetically identical mice, you discover two new independent mutant strains in which all of the animals have epileptic seizures.... You cross a mutant mouse from one strain
to a mutant mouse from the second strain and find that none of their many offspring undergo spontaneous seizures. From this experiment you would conclude that the two mutant strains of mice most likely have mutations in..., students might have misconception about the mutation, specifically about the mutant strains which cause epileptic seizures. Indonesian students chose the incorrect option that the factor that caused the mutation cannot appear in the location of the mutation in the mutant strains and is in different DNA bases rather than genes. In Item 6, this mutation is due to the autosomal recessive inheritance of a single gene on mouse chromosome 13 (Skradski et al., 2001). This mutation is not observed in the offspring, indicating that mutation occurred in the different genes. In this case, one independent mutant strain has the dominant gene, and the other mutant strain has the mutant recessive gene. The misconception in this item might be also supported by confusion about the relationship between DNA and genes in inheritance. Concerning the misconception in the mutation concept, Nusantari (2014) suggested that the lack of molecular evidence of the mutation phenomenon discussed in genetics instruction in Indonesia makes students struggle to correctly interpret mutation cases.

For Item 13, “A man is a carrier for Wilson’s disease (Aa) and Rotor syndrome (Rr). Assume the genes involved in these two disorders are both on chromosome 13 (a non-sex chromosome). Below are possible representations of his genotypes (labeled 1, 2, and 3). Which of them could be correct?” some students experienced difficulty in analyzing phenotypic data to determine the pattern of inheritance. Some students were deceived by the phenotypic data illustrated in the picture, especially 1. The student thought that Wilson’s disease (Aa) and Rotor syndrome (Rr) are inherited from one parent. In reality, to inherit either of the diseases, each parent must have the genotype for the disease, as either the mother will have the recessive allele and the father will have the dominant allele for each disease or vice versa (shown in 2 and 3). Compared to the aforementioned items (Items 1, 5, and 6), Item 13 appeared to be relatively easy, since the percentage of students who chose the correct option was higher. Nonetheless, for students who were thrown off by the distractor, a poor understanding of genetics terminology may have caused challenges in analyzing phenotypic data.

For Item 16, the students had to analyze the pedigree of a family: “Below is a pedigree of a family in which all the people in Generation II are dead (indicated with a slash) because of political unrest in their country. Circles represent females, squares represent males.” This item can be answered correctly if the students know about the principle that mitochondrial DNA is transmitted from the mother alone to her offspring. The sequence of mitochondrial
DNA remains the same over generations since recombination does not occur, and thus it is a useful tool for examining maternal ancestry (Breton, Beaupre, Stewart, Hoeh, & Blier, 2007). However, most of the students likely held a misconception about the mechanism of how a genome is passed on to offspring. While this misconception is generally found among Indonesian students, it is not as common as the misconception about mutations (Nusantari, 2012).

Lastly, Item 19 is a simple question: “Polydactyly is an inherited trait that results in extra fingers or toes. In the US, 0.1% of the population exhibits polydactyly. People with polydactyly have the genotype Pp, where P represents the allele that causes polydactyly and represents the normal allele of this gene. Which of the following true?” The students, however, faced difficulty in interpreting the question. The correct answer (B), “The P allele is less frequent in the US than p allele,” and the distractor (A), “The P allele is more frequent in the US than p allele,” are similar, so students were likely confused by the words “more” and “less” included in the sentences. Looking at the item, 0.1% is a small amount of the population; thus, the occurrence of polydactyly in the United States is less frequent than the normal occurrence (which is 99.9%). Hence, the P allele representing the polydactyly should be less frequent than the p allele representing normal. Some students who answered this item incorrectly might lack the ability to interpret the questions related to the results of molecular analysis.

To conclude, Mustika et al. (2014) and Nusantari (2012) confirmed that Indonesian undergraduate students had misconceptions in certain genetics topics, including the mechanism of inheritance, protein syntheses, reproduction and expression of genetic materials, and mutation. Factors supporting misconceptions in genetics concept can be error reasoning among students, passive learning in genetics instruction, and difficulty to understand complicated terminology and abstract concepts of genetics. Misconceptions have appeared in genetics textbooks and there is a lack of study oriented to molecular biology underlying this condition as well. Accordingly, the Indonesian government and universities is encouraged to take immediate action to conduct curriculum refinement that focuses on these topics. Curriculum refinement can be a starting point to create a better genetics curriculum to improve student performance.

5 Conclusion and Implications

The purpose of the present study was to determine the level of genetics understanding among Indonesian biology majors across academic years and in two
programs. In addition, this study compared genetics understanding between Indonesian and US undergraduate students. The comparison aimed to reflect the quality of Indonesian genetics education on the international scale with the United States serving as a benchmark in order to gain essential information about which aspects of Indonesian genetics education are still lacking in order to develop Indonesian students’ conceptual understanding so as to produce more positive achievement outcomes.

The results of this study showed that academic year significantly affects genetics understanding. Specifically, data showed that students in higher the academic years had higher levels of genetics understanding – which makes sense as these students will have encountered more content over a longer period of time. In contrast to the academic year, the academic program does not significantly affect genetics understanding as the genetics understanding level of biology science students was higher than that of biology education students, but the difference was not statistically significant. Comparative analysis found that US undergraduate students exhibited better genetics understanding than Indonesian students; moreover, there are some items of the GCA that show a large gap between the scores of Indonesian and US students.

Considering these findings, this study has some useful implications for curriculum development and assessment measures in Indonesia. First, this study shows there are both strengths and drawbacks in the Indonesian genetics curriculum. One strength of the Indonesian genetics curriculum is indicated by the finding that “the higher the academic year, the higher the level of genetics understanding” which indicates that the order of genetics courses given to students from first to fourth academic year was able to guide students’ learning progression from a lower to a higher level of genetics understanding. However, when the Indonesian students’ scores were compared to US students’, we found that Indonesian students had a large gap in scores in genetics for topics such as mechanism of inheritance, protein syntheses, reproduction and expression of genetic materials, and mutation. Similar to several locally published studies, this research found that Indonesian students’ assessment performance suggests that the genetics’ curriculum has some drawbacks and a refinement of the curriculum focusing on those topics could be beneficial.

Additionally, this study showed that despite a greater number of and more advanced genetics courses being taken by biology science students, the faculty likely had more impact in guiding students’ genetics understanding than course itself. Finally, international comparative studies among undergraduate students, specifically in the conceptual understanding of a particular subject, need to be conducted more often. The results may highlight issues in particular countries and raise awareness of the main areas that need to be addressed.
Abbreviations

- **CTT**: Classical Test Theory
- **DNA**: Deoxyribonucleic Acid
- **GCA**: Genetics Concept Assessment
- **GDI**: Genetic Drift Inventory
- **IRT**: Item Response Theory
- **LPA-MG**: Learning Progression-based Assessment of Modern Genetics
- **MBCA**: Molecular Biology Capstone Assessment
- **MCDB**: Molecular, Cellular, and Developmental Biology
- **MNSQ**: Mean Squares
- **PISA**: Programme for International Student Assessment
- **RNA**: Ribonucleic Acid
- **TBGC**: Test of Basic Genetics Concepts
- **TIMSS**: Trends in International Mathematics and Science Study

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Ethical Considerations

Ethical approval of the study was granted to Kangwon National University Institutional Review Board which one of the researchers is affiliated (Approval no. KWNUIRB-2017-03-001-002). The board confirmed that the study did not violate human rights and that all contents and processes conformed to the conduct of appropriate research ethics.

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