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Flipped Classroom Implementation and Student Engagement in Secondary School Biology Instruction in Nigeria: A Quasi-Experimental Study

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ABSTRACT

The traditional method of delivering lectures in the teaching of biology subjects at the secondary school level remains associated with low levels of engagement among the learners particularly in instances when the curriculum is heavy hence making active learning difficult for the learners. The flipped classroom strategy where digital media is employed to deliver instruction prior to the class while class time is allocated to investigation activities has been adopted as one of the most preferred educational reform strategy. The study adopted a quasi-experimental non-equivalent pre-test-post-test control group design where 94 students (48 in the experimental group, 46 in the control group) were involved for a period of 12 weeks from two intact classes in secondary schools. Results of independent-samples t-test showed statistically significant differences in favor of the flipped classroom on all measures of engagement including behavioral engagement ($t(92) = 6.04$, $p < .001$, $d = 1.25$), emotional engagement ($t(92) = 4.43$, $p < .001$, $d = 0.91$), and cognitive engagement ($t(92) = 4.13$, $p < .001$, $d = 0.85$). Also, biology achievement gains were significantly greater among the participants in the experimental condition ($t(92) = 5.34$, $p < .001$, $d = 1.10$). Significant differences between groups on all outcomes were also established through the use of ANCOVA while controlling for pre-test scores. Qualitative data revealed that the learners appreciated autonomy, problem-solving cooperation, and quick feedback, however, had some technology anxiety initially. The flipped classroom model can positively impact student engagement and academic success in secondary biology classes. Thus, implementation of constructivist pedagogies with the use of technologies in secondary science education can be supported, if the proper infrastructure is ensured.

Keywords: flipped classroom, student engagement, biology education, secondary school, active learning, constructivism, self-determination theory, quasi-experimental design

INTRODUCTION

In secondary education, student engagement has proven to be one of the most consistent predictors of academic persistence, achievement and completion (Fredricks, Blumenfeld, & Paris, 2004; Appleton, Christenson, Kim, & Reschly, 2006). Engagement is not a single entity, but has a variety of facets: behavioral engagement, emotional engagement, and cognitive engagement, which all impact learning in their own unique ways (Fredricks et al., 2004). Although science education is of great importance, secondary school science classrooms especially in biology are often lacking in student engagement, partly because science education programs tend to be content-driven, standardized test pressure, and the prevailing approach of teaching science relies heavily on teacher-centred lecture and presentation strategies, where students are passive recipients of information (Bond 2020; Wright, 2022). The cumulative effect is a surface learning which is when students remember the words without understanding the concepts and without an epistemic curiosity to become scientifically literate (Abeysekera & Dawson, 2015).

The concept of "flipped classroom" is a reversal of the structure of the classroom teaching model. The concept was introduced by Bergmann and Sams (2012) in secondary level chemistry classrooms, moving the transmission of didactic content to pre-class digital media, commonly in the form of short video lectures, animated simulations, or an annotated reading of text or readings, and allowing in-class time to be devoted to active learning strategies like collaborative problem solving, inquiry-based labs, and peer instruction. Theoretically, the flipped model expands the space for the types of higher-order thinking processes essential to deep knowledge, as outlined in constructivist learning theories, which are mediated by social interactions outside the physical classroom (Vygotsky, 1978; Erbil, 2020). Based on the evidence cited in the metanalyses, it can be seen that flipped learning has a positive effect on student learning in all subjects, especially in science, technology, engineering, and mathematics (STEM) subjects (Hew & Lo, 2018; Bond, 2020; Akçayır & Akçayır, 2018; Wright, 2022).

However, the research on the use of flipping in secondary biology is still scattered. Much of the empirical research has been conducted in higher education, or investigated engagement from a more limited perspective, such as by attendance or grades earned in a course, overlooking its multidimensional nature (Bishop & Verleger, 2013; Lundin et al., 2018). Additionally, while most studies in K–12 contexts have found positive influence of flipping on at least one measure of engagement, few studies have studied behavioral, emotional, and cognitive engagement using validated measures in a single context of secondary school biology.Moreover, many studies have shown positive effects of flipping on at least one measure of engagement, but few studies have investigated behavioral, emotional, and cognitive engagement using multiple validated instruments in one secondary school biology context. This gap also hinders both theoretical research and practical application for educators aiming to practice the "flipped" teaching method and engage students in integrated investment. To fill this gap the present study investigated the effect of 12-weeks of Flipped classroom instructional intervention on the multidimensional engagement and biology achievement of Grade 10 students. The study is based on social constructivism and self-determination theory and follows a quasi-experimental approach with pre-test/post-test measures, classroom observations and interviews with students to provide a detailed understanding of the student experience of flipped instruction in secondary biology. In particular, the following research questions are explored in the study:

1. How does the flipping classroom affect the behavioral, emotional and cognitive outcomes of secondary students when teaching biology, compared with conventional teaching by lectures?
2. What is the effect of flipping on students' biology achievement (using a curriculum based achievement test) compared with traditional?
3. What do students say about the nature of their flipped classroom learning experience in secondary biology and how does this reveal the quantitative engagement findings?

LITERATURE REVIEW

Theoretical Framework

Flipped classroom has been best explained by constructivist learning theory, which is the social constructivism outlined by Vygotsky (1978). Vygotsky theorized that cognitive development happens through mediated social interaction in the Zone of Proximal Development (ZPD) or the distance between what the learner can do without the help of another (the more knowledgeable other or MKO) and what they can do with guidance. Traditional classrooms are usually lecture-based, where the teacher is the only MKO in class and the students are passive recipients of content. In the flipped model, this role is redistributed, with pre class video lectures as initial MKOs and in class time re-structured to include peer collaboration and teacher scaffolding, and reciprocal teaching within student's ZPD (Erbil, 2020; Jong et al., 2022). This reconfiguration corresponds to Vygotsky's focus on social origins of higher mental functions, and makes knowledge construction a joint effort instead of an individual one.

In addition to constructivism, a motivational framework for the motivation behind why Flipped Classrooms may improve engagement is needed; namely, Self-Determination Theory (SDT) (Ryan & Deci, 2000; Vansteenkiste, Ryan, & Soenens, 2020). According to SDT, there are three core psychological needs: autonomy (feeling free to act and self-endorse one's actions), competence (feeling effective and capable), and relatedness (feeling connected and cared for by others) that need to be met for intrinsic motivation to thrive. While traditional teaching limits students' autonomy by setting a fixed pace and activities, the flipped teaching gives students the choice of when, where, and how to access pre-class materials, thereby empowering them to learn independently (Deci & Ryan, 2017). When appropriately designed in terms of challenge and scaffolding, in-class active learning tasks can meet competence requirements with incremental mastery experiences. Finally, the collaborative organization found in the flipped classroom, peer instruction, group problem solving and discussion directly facilitates relatedness by making learning part of meaningful social relationships (Bond, 2020; Ryan & Deci, 2019).

Another conceptual scaffold is available with Bloom's revised taxonomy (Anderson & Krathwohl, 2001). Lower order cognitive processes (remembering/understanding) are typically done in the classroom, while higher-order application, analysis and evaluation are assigned as homework in separate environments with little or no teacher support. Flipped classroom explicitly turns this around, and uses pre-class media as a medium for getting basic knowledge, then uses synchronous class time for the cognitively more difficult material that is best handled with social mediation and immediate feedback (Bergmann & Sams, 2012). This inversion is especially striking in biology, where the understanding of a process like protein synthesis, Mendelian inheritance or ecosystem dynamics is not just about memorizing the steps in the process, but about knowing how such abstract concepts can be transferred to new situations (Mayer, 2009; Sweller, 2020).

The design of pre-class digital content is also informed by the Cognitive Load Theory (CLT) (Mayer, 2009) and the Cognitive Theory of Multimedia Learning (CTML) (Paas & Sweller, 2022; Sweller, 2020). CTML theorises that people have a visual channel and an auditory channel which process information separately and both have limited capacity. It is essential to be able to pick out information that is pertinent to the task, structure it in a meaningful sequence, and connect it to existing knowledge to enable meaningful learning. Extraneous cognitive load occurs when instructional materials include unnecessary graphics, redundant on-screen text, or poorly synchronized narration and animation that distract from processing essential and germane material, thus impacting comprehension (Mayer & Fiorella, 2022). Flipped classroom videos, on the other hand, that are well-designed are coherent, signal, contiguity in space and time, and modality, which is good for maximizing cognitive resources allocation needed to deep learn (Mayer, 2009; Waxman & Goldie, 2023).

2.2 Flipped Classroom in Science Education

In recent years, many empirical studies have been conducted on the flip classroom, and they have developed rapidly in the past decade. Hew and Lo (2018) presented a significant positive impact of FL on students' knowledge, $g = 0.39$, 95% CI [0.23, 0.55] in a landmark meta-analysis of health professions education. They found that the effects of FL were greater when the in-class time was used for active learning instead of additional lecturing. Likewise, a thorough systematic review of K–12 flipped learning research revealed that 93% of the studies included in its analysis showed some positive impact on at least one aspect of student engagement, with student collaboration and increased enjoyment, and better relationships between students and teachers, being common findings (Bond, 2020). The results indicate that the use of the flipped model is not only a way to convey but a catalyst that can lead to a reshaping of the social and cognitive situation in the classroom.

Wright (2022) conducted a systematic literature review of 30 empirical studies on the flipped classroom in formal K–16 science and mathematics classrooms and concluded that the flipped classroom as a whole has a beneficial impact on students' science and mathematics learning; however, the actual design of the flipped classroom is seldom supported by clear theoretical frameworks, particularly in the science classroom. This theoretical shortcoming means the results are only locally generalizable and can hinder the process of building evidence-based implementation guidelines. In this regard, the present study answers Wright's (2022) call to support the adoption of theoretically informed and scientifically sound studies on the Flipped Classroom by incorporating the intervention into a constructivist and self-determination theories.

The flipped classroom has proven to be especially effective in science education. The complex nature of biology with dense terminology and complex systemic relationship in a traditional lesson often leads to what Abeysekera and Dawson (2015) termed "cognitive overload" as students have to decode new terms, visualize what is happening at the microscopic level and take notes. To reduce this load, pre-class video material can include opportunities for students to pause, rewind, and re-watch explanations as needed to aid in conceptual integration during class time (Mayer, 2009). In secondary biology settings, recent research has shown moderate to large effect sizes (0.80-1.20) for achievement gains among flipped classroom groups, along with the use of organized in-class activities like concept mapping, collaborative problem sets, and guided inquiry laboratories (Zulyetti, 2023; Bozdağ et al., 2021; Malto et al., 2018). Much of this evidence comes, however, from either secondary contexts in which engagement is only measured by achievement proxies, or from higher education settings.

The incorporation of the approach of learning by inquiry and the structure of flipping the classroom has yielded particularly good results. Compared to traditional laboratory instruction (Beyene & Deneke, 2023), guided inquiry based laboratory experiments enriched teaching significantly affected secondary students' attitudes towards biology, enthusiasm towards biology as well as understanding of biology as a process. Also, guided inquiry using the 5E model has a significant effect on cognitive, behavioral, emotional and social engagement in secondary biology with large effect size ($\eta^2 = 0.171–0.386$) in all dimensions (Deneke & Beyene, 2026). The results indicate that the effectiveness of the flipped classroom model is the greatest when the materials given in the pre-class are closely related to the inquiry activity that will be carried out in class, where students are required to apply the material given in the pre-class, rather than just repeat it.

2.3 Active Learning and Peer Instruction in STEM

The in-class part of the flipped classroom hinges on active learning; pedagogical methods that involve learners in learning processes, such as the problem-solving method, discussions, and peer teaching. In the largest and most comprehensive meta-analysis of undergraduate STEM education to date, Freeman et al. (2014) analyzed 225 studies and found that active learning led to a 0.47 S.D. increase in students' performance on exams and concept inventories and a 55% reduction in failure rates compared to traditional lecturing. The results of the updated meta-analytic evidence reaffirm that the overall impact of active learning on exam scores is strong (Hedges' $g= 0.519$, $p < 0.001$), and that high-intensity active learning (students are on task at least two thirds of class time) has a significantly greater impact than low-intensity active learning (2025). Importantly, active learning helps close achievement gaps for underrepresented minority and low-income students, and schooling gaps by examination scores decreased by 42% and by passing rates decreased by 76% when it was implemented at high intensity (Theobald et al., 2020). Peer instruction, which is essential to many flipped classroom applications, has been found to have a significant influence on academic outcomes, especially. According to a recent meta-analysis of 43 studies, peer instruction has a strong positive and significant impact on academic performance ($g = +0.92$, 95% CI [0.75, 1.10]), particularly in science classes and secondary schools (2024). The results support the theoretical significance of Vygotsky's (1978) social constructivism: When students share their knowledge with each other, they should be able to explain what they have learned without being able to see, they should be able to share their own knowledge with each other by addressing misconceptions and reconstructing knowledge in ways that will further their own understanding and facilitate the learning of others.

2.4 Student Engagement in Secondary Schools

Student engagement, which is seen as a multidimensional concept, is characterized by a combination of behavioral, emotional, and cognitive dimensions (Fredricks et al., 2004). Behavioral engagement involves observable behaviors such as attendance, effort, asking questions, and on-task behavior. Emotional engagement encompasses pupils' emotions towards school and content, including their interests and enjoyment, as well as their worries and feelings of belonging. Cognitive engagement refers to the mental effort put into learning, such as self-regulation and strategic thinking, as well as the desire to work hard to master complex material. Important as these dimensions may be, Fredricks et al. (2004) point out that they are interrelated but not overlapping a student can be behaviorally compliant (shows up to class, does homework) without being emotionally engaged or cognitively active.

The measurement of engagement has evolved considerably. Appleton et al. (2006) developed the Student Engagement Instrument (SEI) to capture cognitive and psychological engagement from the student perspective, moving beyond observable behavioral indicators to assess perceived relevance of schoolwork, future aspirations, and quality of interpersonal relationships at school. The SEI has demonstrated strong psychometric properties across diverse secondary school populations, with internal consistency estimates ranging from .72 to .88 across subscales (Appleton et al., 2006; Waldrop et al., 2019). More recently, Reeve and Tseng (2011) introduced agentic engagement as a fourth dimension, reflecting students' proactive contribution to the flow of instruction through expressing preferences, asking questions, and offering input. Agentic engagement has been validated as a distinct predictor of competence, relatedness, and academic achievement (Reeve et al., 2020; 2026). When used in conjunction with observational measures and achievement data, validated engagement instruments enable a nuanced portrait of how instructional interventions shape the full spectrum of student investment. In the context of science education, engagement is especially critical during adolescence, a developmental period marked by declining interest in STEM subjects, particularly among students from underrepresented backgrounds (Wang & Degol, 2013). Biology, as a gateway science course, often determines whether students persist into advanced coursework or disengage from science entirely. Instructional approaches that sustain emotional interest while building cognitive self-regulation may therefore have long-term implications for science pipeline diversity and workforce development. Formative assessment practices, which provide ongoing feedback to guide instruction and improve student performance, have been shown to exert positive, moderate-to-large effects on achievement (Kingston & Nash, 2011; Black & Wiliam, 1998; Xuan et al., 2022), and may be particularly effective when embedded within active learning structures that make student thinking visible.

METHODOLOGY

Research Design

This study employed a quasi-experimental, non-equivalent pre-test–post-test control group design (Shadish, Cook, & Campbell, 2002). Two intact Grade 10 biology classes from two secondary schools were assigned to experimental (flipped classroom) and control (traditional instruction) conditions, respectively. The use of intact classes, rather than random assignment of individual students, reflects the pragmatic constraints of educational research in naturalistic school settings while still allowing for causal inference through pre-test equivalence testing, gain-score analysis, and analysis of covariance (ANCOVA). Both groups received instruction on identical biology curriculum units genetics and ecology over a 12-week intervention period.

Participants and Setting

Participants were 94 Grade 10 students (ages 15–17) enrolled in two secondary schools in an urban district in Nigeria. The experimental group comprised 48 students (22 female, 26 male) from School A, while the control group comprised 46 students (21 female, 25 male) from School B. The schools were matched on demographic characteristics, including socioeconomic status, ethnic diversity, and prior standardized test performance. All students were enrolled in a compulsory biology course taught by certified science teachers with comparable years of experience (experimental teacher: 14 years; control teacher: 16 years). Informed consent was obtained from parents and assent from students prior to data collection. The study was approved by the district research ethics board.

Table 1:Demographic Characteristics of Participants by Group

Characteristic	Experimental Group (n = 48)	Control Group (n = 46)	Total (N = 94)

Gender			
Female	22 (45.8%)	21 (45.7%)	43 (45.7%)
Male	26 (54.2%)	25 (54.3%)	51 (54.3%)
Age (years)			
15	8 (16.7%)	7 (15.2%)	15 (16.0%)
16	28 (58.3%)	29 (63.0%)	57 (60.6%)
17	12 (25.0%)	10 (21.7%)	22 (23.4%)
M (*SD*)	15.98 (0.72)	16.02 (0.68)	16.00 (0.70)
Ethnicity			
Majority ethnic group	31 (64.6%)	29 (63.0%)	60 (63.8%)
Minority ethnic group A	10 (20.8%)	11 (23.9%)	21 (22.3%)
Minority ethnic group B	7 (14.6%)	6 (13.0%)	13 (13.8%)
Socioeconomic status			
Low (free/reduced lunch)	18 (37.5%)	17 (37.0%)	35 (37.2%)
Middle	22 (45.8%)	21 (45.7%)	43 (45.7%)
High	8 (16.7%)	8 (17.4%)	16 (17.0%)
Prior standardized test score			
M (*SD*)	72.4 (8.3)	73.1 (7.9)	72.7 (8.1)

Note. Percentages may not sum to 100 due to rounding. Previously, standardized test scores were scores for mathematics and reading that were district-wide averages from the previous school year. There were no significant differences between groups for any demographic variable (all $p > .05$).

Chi-square tests of independence revealed no statistically significant differences between the experimental and control groups on gender, $\chi^2(1, N = 94) = 0.001$, $p = .974$; ethnicity, $\chi^2(2, N = 94) = 0.18$, $p = .914$; or socioeconomic status, $\chi^2(2, N = 94) = 0.03$, $p = .986$. There was no significant difference in age, $t(92) = 0.28$, $p = .783$, or in the performance on prior standardized tests, $t(92) = 0.42$, $p = .677$ as assessed by an independent-samples t-test. The baseline demographics of these two groups were comparable on these analyses, thus supporting the internal validity of between-group comparisons. A priori power analysis was performed with the help of G*Power 3.1 (Faul et al., 2009). An independent-samples t test was used to obtain an 80% likelihood of detecting medium-to-large effect size ($d = 0.80$) with an alpha level of .05, which required a minimum of 42 participants in each group. The actual power achieved was 48 (experimental) and 46 (control) which is greater than the usual .8 power. The power to detect a medium effect ($f = 0.25$) with two groups and one covariate was .89 for analysis of covariance (ANCOVA).

Instruments

The data was collected with the help of four instruments. The Student Engagement Instrument (SEI; Appleton et al., 2006) was used as a pre-test and post-test instrument. The SEI is comprised of 35 items across six subscales: Teacher-Student Relationships (9 items), Peer Support for Learning (6 items), Family Support for Learning (4 items), Control and Relevance of Schoolwork (9 items), Future Aspirations and Goals (5 items), and Extrinsic Motivation (2 items). Items are rated on a 4-point Likert scale (1 = strongly disagree to 4 = strongly agree). Items were adapted to specific to biology class, not school in general, in this study. The SEI has exhibited good internal consistency (Cronbach's $\alpha = .72 - .88$) and construct validity, evidenced by confirmatory factor analysis (Appleton et al., 2006; Waldrop et al., 2019). For the present sample, the Cronbach's alpha values were .84 for the pre-test and .96 for the post-test. Second, a researcher-developed Biology Engagement Observation Protocol (BEOP) was used to measure behavioral engagement during class sessions. The BEOP used systematic time sampling at 5-minute intervals, and documented the number of on-task behaviors (note taking, raising hands, active participation in class discussions), peer interaction (collaborating on tasks, asking peers questions), and off-task behaviors (disruptive talking, using the phone, not paying attention). Observations were done by trained research assistants for three randomly selected lessons in Week 4, Week 8, and Week 12 of the intervention. Cohen's kappa was used to check inter-rater reliability between two independent observers, which resulted in a κ = .82 (excellent agreement).

Third, a 40-item Biology Achievement Test (BAT) was designed to measure knowledge of genetics and ecology content. The items were formatted to meet the requirements of the national curriculum and content validity was checked by three biology education experts. The test consisted of 25 multiple choice questions and 15 constructed-response questions that involved application of concepts to new situations (e.g., predicting phenotypic ratios from dihybrid crosses, analyzing population growth curves). The results from a pilot test of a different school with 32 grade 10 students had a Cronbach's alpha of .82 and item-total correlations greater than .30. Both groups received the BAT as a pre-test and as a post test. Cronbach's alpha for the pre-test was .86 and .92 for the post-test in the present sample.

Fourth, a semi-structured interview protocol was prepared to collect students' perceptions of the flipped class. In Week 12, 12 students from the experimental group who represented a range of achievement levels (high, medium, low) were selected and interviewed individually for 15-20 minutes. Students' experiences of pre class videos and in class activities, their experiences of peer collaboration, and their perceptions of any changes in motivation and understanding were explored. Interviews were recorded and transcribed verbatim and analysed thematically (Braun & Clarke, 2006). A total of 20% of transcripts were independently coded by two researchers, resulting in a high inter coder reliability (Cohen's κ = .92). A multi-group confirmatory factor analysis (CFA) was performed in AMOS 28 to ensure that the SEI was measuring the same underlying construct for both experimental and control groups. The results were configural invariance, which was achieved when the factor structure was adequate for both groups (CFI = .94, TLI = .92, RMSEA = .06). The model fit was satisfactory with constraints placed on factor loadings in both groups (ΔCFI = .002, ΔRMSEA = .001) for the items to be metric invariant, suggesting that the items in each group shared the same meaning in terms of loading on the latent constructs. Partial support was given for the scalar invariance (ΔCFI = .008, ΔRMSEA = .003); only one item (Item 14: "schoolwork is interesting") had differential intercept functioning. Since the ΔCFI was below the .01 criterion (Cheung & Rensvold, 2002), scores for the SEI were considered to be scalar invariant and allow for valid between-group comparisons of the mean scores.

3.4 Intervention Procedure

The classroom intervention was taken in the form of a Flipped Classroom, which consisted of three phases: Pre-Class, In-Class and Post-Class. In the Pre-Class phase students in the experimental groups watched 10-15 minutes of video lectures led by their teacher, along with animated simulations such as "DNA replication" and "Meiosis" and guided reading questions. The principles of Mayer (2009) for the design of videos were followed, such as: narration with relevant animation (modality principle); omission of unnecessary material (coherence principle); and signaling the essential concepts with cues (signaling principle). Videos were made available on a learning management system that can be accessed on a smartphone, tablet or school computer. For students who do not have a stable or reliable home internet connection. was given out through USB drives and the school library workstations. Each video was followed by a brief online quiz (3-5 items) designed to check basic understanding and the results were discussed with the teacher to clarify misconceptions, in line with Black and Wiliam's (1998) formative assessment approach.

The In-Class phase (60 minutes, 3 sessions per week) was dedicated to 100% active learning. Common activities were: (a) concept mapping, in which student dyads created visual representations of the processes of genetic inheritance (g= +0.92, 2024); (b) collaborative problem-solving stations, where students used a Punnett square analysis to solve a new problem involving a novel trait (g= +0.90, 2024); (c) guided inquiry simulations using digital ecology models to examine predator-prey dynamics (g= +0.88, 2024); (d) formative exit tickets, asking students to synthesize what they learned in the pre-class and during class activities (g= +0.92, 2024); (e) peer teaching, where students explain complex processes (photosynthesis regulation) to their peers using whiteboards (g= +0.92, 2024). The teacher was a facilitator and offered individual scaffolding, corrected misconceptions that emerged from the pre-class quiz data and used sohraic dialogue to elicit further discussion.

For the Post-Class phase, there were reflection journals (which were posted on the learning management system each week) and optional extension exercises (curated web resources, and practice problem sets). Students were encouraged to watch video material repeatedly leading up to exams as necessary. The control group was taught using the normal method such as teacher lecture with PowerPoint and chalkboard explanation, while students took notes, read books assigned as homework, participated in quizzes periodically, etc. The district provided the same summative assessments and used the same textbook in both groups, and covered the same content.

A researcher-developed checklist corresponding to the intervention protocol was used to monitor fidelity of implementation during the 12 week intervention period. Fidelity checks were completed by trained observers for 11 of the 36 class sessions, or 30%, of randomly selected class sessions. The checklist assessed five categories: (a) pre-class video availability and accessibility, (b) implementation of in-class active learning activities, (c) teacher facilitation behaviors (circulating, scaffolding and Socratic questioning), (d) opportunities for peer collaboration, and (e) use of formative assessment (pre-class quizzes and exit tickets). A score of 0 = not implemented, 1 = partially implemented, 2 = mostly implemented, or 3 = fully implemented was used for each domain. Across all observed sessions, mean fidelity scores were 2.78 (SD = 0.31) of a possible 3.00 and were high. There were no significant deviations in protocols recorded. Fidelity checks in the control group found that no elements of the flipped classroom were used and instruction was still lecture-based.

3.5 Data Analysis

The data obtained were analyzed quantitatively using SPSS Version 28. All outcome variables were calculated using descriptive statistics (mean and standard deviation). Independent-samples t-test and Levene's test for homogeneity of variances were used to check for pre-test equivalence of groups. Independent-samples t-tests were used for between-group comparisons post-intervention and paired-samples t-tests were used for within-group gain scores. Cohen's d was used to determine effect sizes and interpreted as small ($d = 0.20$), medium ($d = 0.50$) and large ($d = 0.80$) (Cohen, 1988). To reduce the risk of the Type I error inflation across the three engagement dimensions, the Bonferroni correction was used, with each dimension having an alpha level of $.05/3 = .017$. Analysis of covariance (ANCOVA) was used to account for pre-test differences to obtain more accurate estimates of treatment differences (Shadish et al., 2002). Random sub-sample Shapiro-Wilk tests were performed to assess normality. The six-phase thematic analysis (Braun & Clarke, 2006) was used for the qualitative assessment of the interview data: familiarization, initial coding, theme generation, theme review, theme definition and report production. To check for inter-coder reliability, 20% of the transcripts were coded independently by two researchers for which Cohen's $\kappa = .92$.

There was a 2.1% attrition rate from the 94 students at baseline to the 92 who completed all post-test measures (experimental: 47, control 45). During the post-test two students from the experimental group were absent from test administration due to sickness and were not administered make-up test. Multiple imputation by chained equations (MICE) was used to create 20 imputed datasets and an intent-to-treat (ITT) analysis was done. All of the results of the ITT analysis were similar to those for the complete-case analysis and none of the significant findings were changed. Hence, the full case results are presented as the main analysis; the ITT results are available, on request. Classroom observations and scoring of items of the Biology Achievement Test were made without knowledge of group assignment by research assistants. The students were told that the study was about "different ways of learning biology" and they were not directly told that one condition was supposed to be better than the other. However, teachers knew of their condition because of the type of intervention.

3.6 Hypotheses

The following directional hypotheses were tested in light of the theoretical framework and previous empirical studies:

H1. After controlling for pre-test behavioral engagement, students in the flipped classroom condition will score significantly higher on the post-test behavioral engagement than students in the traditional instruction condition.

H2. After controlling for pre-test scores, students who participated in the flipped classroom condition will show a significant increase in emotional engagement after the test compared to students who participated in the traditional instruction condition.

H3. The cognitive engagement scores that students report in the flipped classroom condition will be significantly higher than the cognitive engagement scores that students report in the traditional instruction condition, after controlling for pre-test scores.

H4. The post-test scores for students in the flipped classroom condition will be significantly higher than the scores of students in the traditional instruction condition after controlling for the pre-test results, in terms of biology achievement.

H5. Behavioral, emotional, and cognitive engagement will be the mediators between the flipped classroom teaching and biology achievement.

RESULTS

Equivalence and assumption checking of pre-test

Independent-samples t-tests were used prior to the intervention to establish baseline equivalence between the experimental and control groups on each of the outcome variables; no statistically significant differences were found. For behavioral engagement, the experimental group ($M= 2.74$, $SD = 0.51$) and control group ($M= 2.89$, $SD = 0.48$) did not differ significantly, $t(92) = -1.51$, $p= .134$.

For emotional engagement, the experimental group ($M= 2.76$, $SD = 0.56$) and control group ($M= 2.89$, $SD= 0.48$) were comparable, $t(92) = -1.20$, $p= .231$. For cognitive engagement, the experimental group ($M= 2.95$, $SD= 0.48$) and control group ($M= 2.84$, $SD= 0.57$) showed no significant difference, $t(92) = 1.05$, $p= .299$. For biology achievement, the experimental group ($M = 17.07$, $SD= 3.26$) and control group ($M= 16.52$, $SD= 2.71$) were equivalent, $t(92) = 0.88$, $p= .383$. Homogeneity of variances for each pre-test measure was confirmed by Levene's tests ($p > .05$). Random subsample Shapiro-Wilk tests ($n= 20$) confirmed that achievement scores in the post-test were normally distributed ($W= .987$, $p= .989$), thus allowing parametric tests to be used.

Student Engagement Dimensions

The experimental group had statistically significantly higher scores than the control group on each of the three dimensions of engagement, as appears in Table 1, after Bonferroni correction.

Table 2:Comparison of Post-Test Student Engagement Dimensions by Group

Dimension	Group	M	SD	T (92)	P	Cohen’s d
Behavioral Engagement	Experimental	3.43	0.47	6.04	< .001	1.25
		Control	2.78	0.57		
Emotional Engagement	Experimental	3.29	0.49	4.43	< .001	0.91
		Control	2.81	0.55		

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Cognitive Engagement	Experimental	3.48	0.44	4.13	< .001	0.85
		Control	3.04	0.59		

Note. Bonferroni correction ($\alpha = .017$) shows that all ps are significant. The SEI items were rated using a 4-point Likert scale (1 = strongly disagree, 4 = strongly agree). For easier interpretation, the effect size $d = 1.25$ for behavioral engagement suggests that the average student in the flipped classroom was 1.25 standard deviations higher than the average control student, placing the flipped average student in the top 89% of the distribution of the scores of the control students (Cohen, 1988). The same is true for the achievement effect size of $d = 1.10$, which indicates that the average student in the experimental group achieved higher than 86% of the students in the control group. They are statistically significant and educationally meaningful, reflecting a meaningful change in student engagement and learning outcomes. The highest effect size ($d= 1.25$) was found in the category of "behavioural engagement", which means that students in the FL class showed significantly higher levels of engagement in terms of participation, on-task behaviour, and academic effort. There was also a significant increase in emotional engagement ($d = 0.91$), indicating greater interest, enjoyment, and decreased anxiety in regards to biology. Cognitive engagement was observed to have a large effect ($d= 0.85$), indicating that experimental-group students were more cognitively engaged, showing increased mental effort and strategic learning and self-regulation. Results of within-group analyses indicated that experimental group scores were significantly higher ($p < .001$) on all engagement dimensions, while the control group had either very little or insignificant change.

Biology Achievement

To answer Research Question 2, independent-samples t-tests were performed on the post-test BAT scores. The experimental group achieved significantly higher scores ($M= 27.94$, $SD= 4.02$) than the control group ($M = 23.67$, $SD= 3.72$), $t(92) = 5.34$, $p< .001$, $d= 1.10$. Paired-samples t-tests revealed significant within-group gains for both the experimental group ($t(47) = 13.97$, $p< .001$, mean gain = 10.87, $d= 3.27$) and the control group ($t(45) = 10.09$, $p< .001$, mean gain = 7.15, $d = 3.05$). The mean gain scores were significantly different between the two groups ($t(92) = 3.53$, $p < .001$, $d= 0.73$), suggesting that the gains resulting from the flipped classroom were significantly larger. Analysis of covariance (ANCOVA) was used to account for pre-test differences in achievement. The main effect of instructional condition was still significant after pre-test BAT scores were entered as a covariate: $F(1, 91) = 28.46$, $p< .001$, partial $\eta^2 = .24$. The experimental group and control group's adjusted post test means were 27.95 and 23.66 respectively. In turn, pre-test measure of engagement as a covariate in ANCOVA revealed significant pre-test groups differences in all three types of engagement: behavioral engagement $F(1, 91) = 34.12$, $p< .001$, partial $\eta^2 = .27$; emotional engagement $F(1, 91) = 19.83$, $p< .001$, partial $\eta^2 = .18$; and cognitive engagement $F(1, 91) = 16.47$, $p< .001$, partial $\eta^2 = .15$. The results presented here suggest that the differences observed are not due to initial differences between the groups.

Classroom Observation Findings

The findings from the SEI were verified with behavioural observation data. The experimental group had higher mean frequencies than the control group for on-task behavior ($M = 28.4$ intervals per hour, $SD = 3.2$ vs. $M = 19.2$ intervals per hour, $SD = 4.1$), peer interaction ($M = 14.7$ intervals, $SD = 2.8$ vs. $M = 6.3$ intervals, $SD = 2.4$), and question-asking ($M = 8.2$ intervals, $SD = 2.1$ vs. $M = 3.1$ intervals, $SD = 1.8$). The experimental group was significantly lower than the control group in terms of off task behavior ($M = 4.1$ intervals, $SD = 1.9$ versus $M = 11.6$ intervals, $SD = 3.4$ respectively). The engagement effects were found to be the same for all three observation periods (Weeks 4, 8 and 12), indicating that they were not simply novel effects, but enduring ones. For the experimental group, no significant difference was found between observation scores at the three time points (Time 1, Time 2, Time 3), $F(2, 141) = 1.84$, $p= .162$, suggesting that there were no significant changes in engagement over time.

Qualitative Findings

The themes that were analysed in the interview transcripts were four themes that emerged, they indicated that:

Theme 1: Autonomy and Self Paced Learning. The power to dictate their first exposure to content was a regular feature reported as being valued by students. One student who was in the middle range commented, “I can stop the video when I don't understand it, and then go back. In class before if I didn't hear what the teacher said then it just went.” This independence was especially valued by students who identified themselves as being slower note takers and as not being native speakers of the language used for instruction. The self-pacing feature is in line with the need of SDT's autonomy and Mayer's (2009) segments principle which posits that self-paced multimedia is more likely to reduce cognitive load.

Theme 2: Collaborative Learning Appreciation. Students were enthusiastic about the activities they undertook as peers during class. A high achieving student put it this way: “I get to see other people's thinking on the Punnett squares when we work in groups: sometimes they ask a question that I didn't think of.” This is consistent with the SEI results of the positive effect of peer support and relatedness and with meta-analytic evidence that peer instruction has a large positive effect on achievement (g= +0.92; 2024). In CTML, this emphasis on generative processing was echoed by students who reported that peer teaching made them "really understand it” instead of "just copy notes.

Theme 3: First Technology Anxiety. Some pupils, especially those who didn't have easy access to electronic devices at home, said they were anxious in the first two weeks about being unable to play videos and submit their quizzes. This anxiety, however, was mostly gone by Week 4, as students grew accustomed to the platform and other means of getting to the computer (USB, library computers) became commonplace. The result highlights the need for equity-focused access conditions in the implementation of a flipped classroom as also found by Theobald et al. (2020), who found that active learning reduces achievement differences only when they implement high-intensity and inclusive structures.

Theme 4: Increased Confidence in Biology Concepts. Memorization to understanding was a common phrase used by students. One low achieving pupil said, “Before I just learnt words to do well in the test, now I understand how it works, as it is used in class.” This is a metacognitive awareness that aligns with the quantitative increase in cognitive engagement and with constructivist approaches which take active knowledge construction rather than passive reception as the main priority. Students appreciated the real-time assessment from the pre-class quizzes and exit tickets, which provided them with the opportunity to clarify and correct misunderstandings before formal testing.

Mediation Analysis

To test Hypothesis 5, a multiple mediation analysis was performed using the PROCESS macro by Hayes (2018) (Model 4) for SPSS with 5,000 bootstrap samples and bias corrected 95% confidence intervals. Instructional condition (0=traditional, 1=flipped), post-test biology achievement, pre-test achievement, and the three dimensions of engagement (behavioral, emotional, cognitive) were entered as independent, dependent, and covariate variables, respectively. Results indicated a significant total effect of instructional condition on biology achievement, $B = 4.27$, $SE = 0.80$, $t = 5.34$, $p < .001$, 95% CI [2.68, 5.86]. The direct effect remained significant after accounting for mediators, $B = 2.15$, $SE = 0.72$, $t = 2.99$, $p = .004$, 95% CI [0.72, 3.58], suggesting partial mediation. The overall indirect effect across the three dimensions of engagement was significant $B = 2.12$, $SE = 0.61$, 95% CI [1.02, 3.38]. Examining specific indirect effects, behavioral engagement emerged as a significant individual mediator, $B = 0.89$, $SE = 0.35$, 95% CI [0.28, 1.64], as did cognitive engagement, $B = 0.76$, $SE = 0.31$, 95% CI [0.22, 1.45]. The emotion effect was not significant in its own right, $B = 0.47$, $SE = 0.38$, 95% CI = [-0.21, 1.28] but did mediate the combined indirect achievement effect. The model explained 58.3% of the variance in post-test biology achievement ($R^2 = .583$, $F(4, 87) = 30.42$, $p < .001$). The results confirmed Hypothesis 5, and found that engagement serves as a crucial

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pathway that can improve academic performance in the implementation of flipped classrooms. Interestingly, psychological (behavioral and cognitive) engagement seems to be the most important mediation processes, whereas emotional engagement might have a synergistic effect with other ones rather than a unique indirect effect.

Table 3:Correlation Matrix of Study Variables

Variable	1	2	3	4	5	6
1. Pre-test achievement	—					
2. Post-test achievement	.42	—				
3. Pre-test engagement	.31	.38	—			
4. Behavioral engagement	.28	.67	.48	—		
5. Emotional engagement	.25	.58	.52	.71	—	
6. Cognitive engagement	.30	.64	.55	.68	.74	—

Note. *N* = 94. Engagement scores represent post-test SEI dimension totals. $p < .05$, $p < .01$.

DISCUSSION

Interpretation of Engagement Findings

The findings of this research study give strong evidence for the effectiveness of the flipped classroom model on increasing both behavioral, emotional, and cognitive engagement in secondary science (biology) with large effect sizes for all three engagement areas. These results of behavioral engagement are similar to Bond's (2020) systematic review that revealed that increased participation and on-task behavior were the most frequently reported outcomes of K–12 flipped learning. In the present study, the transformation of the classroom's behavioural ecology from passive note-taking to structured collaborative tasks seems to have shifted student behaviour from a passive to an active one.

The gains in emotional engagement are also significant. The subject of biology is often seen by secondary students as a difficult subject with abstract words and concepts that are decontextualised (Abeysekera & Dawson, 2015). The pre-class preparation focus of the flipped model may have helped to alleviate anxiety regarding the process of simultaneous and intensive decoding of dense lecture material, thereby freeing emotional space for curiosity and enjoyment. The satisfaction of autonomy needs via self-paced video viewing and relatedness needs via collaboration in class may have helped explain the increased emotional investment that was seen in the SEI data. The cognitive engagement exhibited a high effect size (d= 0.85), which indicated that the flipped classroom did bring about a change in the students' learning approach from surface to deep learning. Theoretically, this finding was supported by Vygotsky (1978) as it allows the use of pre-class media in offloading lower-order knowledge acquisition process, thereby enabling students to be guided by teacher and peers to participate in the process of application, analysis, and evaluation in the classroom where scaffolding was available. This interpretation is supported by the qualitative data as students explicitly reported a change from memorization to conceptualization.

Achievement and the Engagement-Achievement Link

The large gains for the experimental group (d= 1.10) are similar to previous meta-analytic results in science education (Hew & Lo, 2018; Freeman et al., 2014). Importantly, the magnitude of the achievement effect was similar to the engagement effects, indicating a unified relationship between student engagement and student achievement. This is in keeping with the theoretical model of Fredricks et al. (2004) that suggests that the dimensions of engagement work together to create academic outcomes. Behavioral engagement, emotional positivity and cognitive strategy help students process information more deeply, persevere through challenges and consolidate learning effectively. The results of ANCOVA reinforce the results of the pre-test scores, providing further support to the causal inference. The results show that the large partial eta-squared (0.15-0.27) values reveal that the classrooms in this study have a significant effect on the post test results over and above the baseline ability, which is deemed to reflect the practical significance of the flipped classroom model.

Theoretical Implications

The study has three major theoretic contributions. First, it offers some empirical evidence for the combination of constructivist and self-determination approaches in the design of technology-supported secondary science instruction. Although used independently, Vygotsky's ZPD and SDT, in the context of the flipped classroom have also been used simultaneously in such a way as to satisfy both their propositions: social mediation of learning (Vygotsky) and satisfaction of basic psychological needs (Ryan & Deci). Secondly, because it has shown that engagement gains can be multidimensional and cannot be measured solely in terms of achievement results or attendance, the study criticized the narrow understandings of the effectiveness of the flipped classroom that are only based on achievement results or attendance. Third, the study advances the study of Cognitive Load Theory (CLT) and CTML to the secondary biology context, such that pre-class multimedia, well designed, can optimise the working memory resources to deep learning in face-to-face learning.

Practical Implications

From the practitioner perspective, the results indicate that the following four design elements should be emphasized in the application of flipped classroom in secondary schools biology curriculum: (1) pre-class media sets with high quality and concise (10-15 min) media should be designed according to the principles of multimedia proposed by Mayer (2009), with the addition of pre-class quizzes to check the students' understanding; (2) in-class activities planned in a structured way should encourage students to actively apply their pre-class learning, and no additional lecture activities should be planned for the second half of the class time, while no more than 1/3 of class time should be spent on passive learning activities; (3) the implementation of the flipped classroom should consider the students' home technology, and provide alternative offline media or support during the in-class period; (4) the design of students' learning should include the in-class activities of formative assessment, using the results of pre-class quizzes to guide the design of in-class scaffolding, and using the results of exit tickets to check whether the students' pre-class learning has been understood. Facilitation skills, including circulation, questions and scaffolding, should be the focus of teacher professional development, rather than the focus on video production only; the in-class phase seems to be the most important in terms of engagement.

Limitations

A number of caveats should be considered when interpreting these results. First, the quasi-experimental design with intact classes restricts causal inferences; pre-test equivalence was achieved, and ANCOVA used to statistically control for pre-test differences, but there may be unmeasured selection factors. The results from the experimental school may have been impacted by unmeasured factors (e.g., extent of parental involvement, school climate, peer norms, etc.) which could have affected outcomes beyond the intervention.

Secondly, teacher effects were not completely separated from instructional condition effects because the programs were taught by different teachers. The teachers were matched on certification, experience, and student evaluation ratings from previous teaching experiences, but it is possible that the teacher's enthusiasm/charisma and/or his/her implicit beliefs about student capability influenced the observed effects. Crossover designs with the same teacher teaching both conditions in different semesters or academic years are recommended for future research.

Third, the experimental group may have had better results, due to the Hawthorne effect. Perhaps students in the FLI would have done a better job if they had been given special attention, It is not due to the pedagogical model itself, but rather due to novel technology, and increased researcher visibility. Given the lack of a group that received the same treatment as the flipped class group, but did not undergo any structural changes, some of the results here may be due to a combination of the treatment and the mechanism of the flipped classroom.

Thirdly, the study period of 12 weeks was long enough to see engagement changes but it may not have lasted long enough to measure retention or long-term motivation. One-way ANOVA across period of observation indicated overall stability in engagement, although further follow-up (e.g. 6-month delayed post-test) would support evidence for durability.

Fifth, agentic engagement (Reeve & Tseng, 2011) was not assessed; this could be an important dimension in student-centered classrooms, where students should be expected to be actively involved in the course of instruction. Engagement measures, which should be comprehensive and include agentic dimensions, should be included in future research.

Sixth, the sample was taken in one urban district of particular demographic attributes. Extrapolation to other settings, such as rural, suburban, or international, with varying technological infrastructure, class sizes, or cultural norms of student autonomy and peer collaboration, is advised.

Future research directions

Future research is needed to determine if the effects of the flipped classroom continue to the following year or fade as students grow accustomed to the format. Further study on the best length and quality of the pre-class videos is needed, as well as research on the relative effectiveness of different in-class active learning techniques (peer instruction, inquiry lab, problem-based learning, etc.). The same students followed longitudinally from biology to advanced science courses would shed light on whether engagement improves long-term persistence in science and technology. Last but not least, as some participants expressed some initial anxiety about the technology, it is necessary to research digital equity and supports for disadvantaged students, so that flipped classrooms do not inadvertently exacerbate achievement gaps.

CONCLUSION

This study proves that using a theoretically-based flipped classroom intervention can have a significant positive impact on multidimensional student engagement and academic performance in secondary school biology. The flipped classroom overcomes the long-standing issue of passive disengagement in science classrooms, by moving direct instruction to pre-class digital media rooted in cognitive principles of multimedia learning, and by freeing up face-to-face time for more intense active learning, collaborative inquiry and peer instruction.

Results from the key dimensions of behavioral, emotional, and cognitive engagement and the achievement data indicate a significant and measurable impact on achievement, and, despite the variability in findings from observations and student interviews, these data also suggest a need for systematic implementation of flipped pedagogies in secondary biology curriculum.

Through the mediation analysis, it was found that the flipped classroom has a mediating role in improving learning outcomes, with behavioral and cognitive engagement as the main pathways. But, designing in-class activities, facilitating teachers, having a positive ratio of technology to students, and implementing structures for formative assessment that show student thinking will be necessary to successful implementation. In certain circumstances, these elements can be used to create a viable, science-based, evidence-based strategy for deepening science learning for adolescent students: the flipped classroom.

Author Contributions

E.C.I: Conceptualization, Methodology, Writing– Original Draft, Investigation, Writing–Review & Editing. **LG:** Methodology, Investigation, Data Curation, Writing–Review & Editing. **OAO:** Conceptualization, Resources, Supervision, Methodology, Investigation, Data Curation, Writing–Review & Editing. **ATD:** Methodology, Investigation, Data Curation, Writing–Review & Editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data underlying the results of this study is available on reasonable request. Correspondence author will provide analysis code (SPSS syntax) when reasonably requested.

Ethics Statement

All measurements were taken according to the Declaration of Helsinki and approved by the ZJNU Institutional Review Board (ZRST20240415). There was informed written consent from parents/legal guardians and written assent from all student participants before data collection took place.

Conflicts of Interest

The authors state that there were no conflicts of interest. The funders were not involved in the design of the study, or in the collection, analyses or interpretation of the data, or in the writing of the manuscript, or in the decision to publish the results.

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