RESEARCH ON LEARNING

Which Way Is Better? Comparison of Two Interactive Modeling Approaches for Teaching Meiosis in an Introductory Undergraduate Biology Course

RECOMMENDED FOR *AP Biology*

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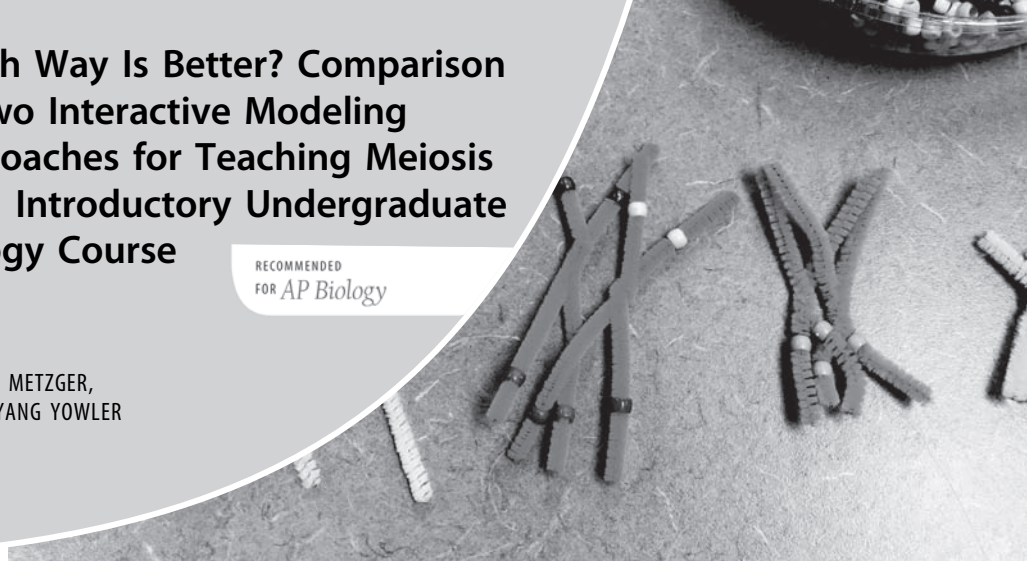

Abstract

The processes of mitosis and meiosis are oft-cited and long-standing examples of concepts that are difficult for students to learn and understand. While there are many examples in the literature of "how-to-do-it," innovative instructional approaches for teaching mitosis and meiosis, publications that include measurement of learning gains are fewer. Moreover, when measurement of learning gains are reported, the outcomes of innovative approaches are most often compared to outcomes from traditional lecture-format instruction. In contrast, this research compares two active-learning approaches to teaching meiosis through modeling in an introductory undergraduate biology course for health sciences majors. Items from the published, validated Meiosis Concept Inventory were used for pre- and post-instruction assessment. In addition, we collected data regarding student perceptions of the learning experience in each modeling scenario through two Likert-scale items and two free-response items. Overall, students demonstrated significant learning gains from pre- to post-assessment. We found no significant differences in performance on the posttest between the two modeling approaches, indicating that the selection of the modeling activity used to support student learning can be made on the basis of other criteria, such as instructor preference, physical classroom layout, or available supplies.

Key Words: *Active learning; student-centered teaching; mitosis; meiosis; cell division; student performance; Meiosis Concept Inventory; modeling; curriculum design.*

○ Introduction

Instruction in mitosis and meiosis is ubiquitous in biology education. However, it is well documented that students harbor misconceptions concerning these cellular processes at the middle school (Williams et al., 2011), high school (Stewart, 1982, 1983; Stewart et al., 1990; Lewis et al., 2000a, b, c; Öztap et al., 2003; Kara & Yesilyurt, 2007), and undergraduate levels (Kindfield, 1991, 1993, 1994; Smith, 1991; Quinn et al., 2009; Newman et al., 2012; Ozcan et al., 2012). Misconceptions have also been reported in a study of prospective biology teachers (Kargöz & Çakir, 2011). Thus, learners at all levels struggle to differentiate key mechanistic differences between mitosis and meiosis – and the consequent biological differences in the cells that result from meiosis – leading to difficulty in connecting these concepts to genetic variation, Mendelian inheritance, and evolutionary processes.

The dynamics of genetic recombination and cell division are indeed quite complex, and geneticists continue to investigate the intricacies of meiosis (Page & Hawley, 2003, 2004; Mézard et al., 2015). Nevertheless, a solid grasp of these foundational genetics concepts is requisite knowledge for students to progress to a sophisticated understanding of the sources and inheritance of genetic variation across generations. Biology educators at all levels are thus well served by being familiar with common conceptual hurdles that students may need to surmount, and by evaluating instructional strategies that can be employed to facilitate student understanding of these challenging concepts.

The assessment approaches taken here can serve as a general model for evaluating the effectiveness of active-learning approaches and can be applied to diverse content areas.

There are many examples in the literature of "how-to-do-it," innovative instructional approaches to teaching meiosis. In our survey of published articles, we identified three broad categories of innovative teaching practices: (1) drawing with pencil and paper (Mertens & Walker, 1992); (2) using manipulative models (Mathis, 1979; Coleman, 1986; McKean & Gibson, 1989; Oakley, 1994; Levy & Benner, 1995; Stencel, 1995; Clark & Mathis, 2000; Harrell, 2001; Lock & McDermid, 2005; Stavroulakis, 2005; Chinnici et al., 2006; Wright & Newman, 2011; Luo, 2012); and (3) students physically assuming the identity of a cellular component to act out cell division through movement of their bodies (Chinnici et al., 2004; Kreiser & Hairston, 2007). Articles describing modeling in teaching mitosis and meiosis use a variety of materials (Table 1).

The American Biology Teacher, Vol. 81, No. 2, pp. 98–109, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2019.81.2.98.

Table 1. Summary of published mitosis and meiosis modeling instructional approaches. Columns on the right half of the table indicate whether the article reports a measure of student performance and/or data regarding student perceptions of the instructional approach described. When such information has been included in the article, a brief description is provided.

Reference	Materials Used in Modeling Approach	Student Performance Data Included in Article?	Student Perceptions Data Included in Article?
Mathis, 1979	Audio tapes and manipulable cell models	Yes, 5 knowledge-recall items, 5 comprehension- or application-level items	Yes, Likert scale
Coleman, 1986	Wooden clothes pegs	No	No
McKean & Gibson, 1989	Paper, paper clips, and string	No	No
Oakley, 1994	Sweat socks	No	No
Levy & Benner, 1995	Ribbons	No	No
Stencel, 1995	String and paper	No	No
Clark & Mathis, 2000	Yarn, pipe cleaners, clothesline and Petri dishes	No	Yes, Likert scale and free response
Harrell, 2001	Velcro, yarn, and adhesive notes	No	No
Chinnici et al., 2004	Students as "human chromosomes"	Yes, responses to "bonus" questions on exam for extra credit	Anecdotal, two student comments from written feedback
Lock & McDermid, 2005	Pool noodles	No	Unsolicited student feedback on teaching evaluations
Stavroulakis, 2005	Sweat socks	No	Anecdotal
Chinnici et al., 2006	Sweat socks	No	Yes, course evaluation comments
Kreiser & Hairston, 2007	Students as "human chromosomes"	Yes, exam scores	No
Wright & Newman, 2011	Sweat socks	Yes, exam items and student interviews	No
Luo, 2012	Springs	No	Yes

However, publications that include measurement of learning gains using such approaches are fewer; more commonly reported are positive student responses (see Table 1), which offer limited evidence of the effectiveness of the approach. Moreover, when measurement of learning gains associated with described practices is reported, the outcomes of a single innovative approach are most often compared to outcomes from lecture-based instruction (see, e.g., Wright & Newman, 2011). As evidence for the effectiveness of student-centered, active teaching and learning approaches over traditional lecture approaches continues to mount (Freeman et al., 2015), investigations of alternative methods of active learning are needed to gauge relative efficacy, so that best practices and approaches to active learning broadly and for specific content areas can be elucidated. As such, the present study investigates and compares learning gains between two modeling approaches to teaching meiosis in two lecture sections of an introductory undergraduate biology course for health sciences majors. The goal of this investigation was to determine whether one modeling approach led to greater learning gains compared to the other or, rather, the two approaches yielded similar outcomes for student learning and could thus be interpreted as equally appropriate alternatives for teaching the same concepts. The modeling approaches used in this study address student misconceptions regarding meiosis, especially reinforcing the particulate, physical nature of genetic loci. We hypothesized that students would demonstrate significant learning gains from pre- to post-assessment, regardless of the active-learning approach taken. Although we were interested in whether the modeling approaches produced a difference in learning gains, we had no a priori hypothesis that one approach would be more efficacious than the other. The results of this study are intended to inform instructional design choices at our institution, and to inform the biology education community more broadly. While this study focuses on evaluation of active-learning strategies for teaching meiosis through modeling, the assessment approaches taken here can serve as a general model for evaluating the effectiveness of active-learning approaches, including the use of validated instruments to

document student learning as a result of instruction, and can be applied to diverse content areas.

○ Methods

This quasi-experimental trial comparing two active-learning strategies for learning meiosis took place within the context of a health sciences undergraduate degree program (Bachelor of Science in Health Sciences, BSHS) at a small liberal arts university in the Midwest. Students entering the program are mostly traditional-aged college students. According to institutional data, ~72% of students in the program identify as female, and 20% identify as institutionally under-represented minorities (URM), a designation that includes the categories Asian, Black, and Hispanic. All participants consented to participate in this research in accordance with University of Minnesota IRB protocol no. 1008E87333.

Study subjects were students enrolled in two sections of a five-credit, first-year, foundational biology course with lab. Students enroll in this course during the second semester of their first year, which means they have completed one semester of college coursework in the program. Due to the cohort nature of enrollment in the program, students take courses in a prescribed sequence, particularly in the first and second years of the program. As such, there are very few non-degree-seeking students or students who are not in their first year of college coursework enrolled in the course. The same instructor taught all sections of the course. Instruction took place in an active-learning classroom (Dori & Belcher, 2005; Beichner et al., 2007; Dori et al., 2007; Walker et al., 2011) and using a flipped pedagogy model. The physical classroom environment and curricular design facilitated regular implementation of a variety of teaching and learning activities and classroom assessment techniques (CATs; Angelo & Cross, 1993). In preparation for classroom instruction and activities, both lecture sections were assigned pre-instruction reading with corresponding preparation questions (i.e., study guide questions). Additionally, students completed a low-stakes pre-class quiz consisting of five questions related to the material in the assigned reading. Students were allowed two attempts on the pre-class quiz and were able to see which items they answered correctly or incorrectly immediately after submitting the quiz. Supplementary materials posted on the course website included slides, links to online conceptual animations, and practice questions. In conjunction with the instruction that took place during lecture sections, all students enrolled in the lecture also completed a laboratory instruction component involving handouts for paper-and-pencil depictions of mitosis and meiosis.

During classroom instruction, lecture section A experienced a 45-minute meiosis lesson incorporating role playing, with socks held by students representing chromosomes and small beads placed on safety pins attached to the socks to represent genetic loci. This lesson incorporated elements of previously published modeling using socks (Stavroulakis, 2005; Wright & Newman, 2011), with the addition of safety pins with small craft beads placed on them to represent genetic loci (see Appendix 1; Appendices 1–3 are available as Supplemental Material with the online version of this article). Students used these materials to model provided diploid genotypes for several loci on different chromosomes and to physically act out the behavior of chromosomes during DNA replication, mitosis, and meiosis. Lecture section B experienced a 45-minute meiosis lesson utilizing manipulative modeling with pipe cleaners of varying sizes to represent chromosomes and small craft beads placed on the pipe cleaners to represent genetic loci (see Appendix 2). Similarly, students in this treatment group used their materials to model provided diploid genotypes for several loci on different chromosomes and to physically act out the behavior of chromosomes during DNA replication, mitosis, and meiosis. Outside of this 45-minute instruction block, the students experienced identical learning scaffolding (e.g., Appendix 3).

Demographics of Lecture Sections

To determine if there were significant differences between the lecture sections with regard to demographic or incoming performance metrics, statistical analyses were conducted for all variables for which data were available. To determine if there was a significant difference between the distribution of gender (male/female) or ethnicity (non-URM/URM) in the two lecture sections, a two-tailed Fisher's exact test was used. To determine if there was a significant difference in incoming performance metrics between the two lecture sections, two-tailed t-tests were performed using comprehensive ACT scores and cumulative college GPA.

Assessment of Student Learning Gains: Meiosis Concept Inventory Subset

Items from the published, validated Meiosis Concept Inventory (MCI; Kalas et al., 2013) were used for pre- and post-instruction learning assessment. The MCI was designed as both a diagnostic tool and an assessment instrument (Kalas et al., 2013). It was implemented here to assess student learning resulting from the two modeling approaches. The 17-question MCI inventory has been validated in a population of introductory biology and genetics university students (Kalas et al., 2013). An eight-item subset (questions 1, 2, 4, 13, 14, 15, 16, and 17) of the inventory has been used for pre-/post-assessment of student learning in the university classroom (Kalas et al., 2013, p. 660). For example, learning gains (normalized change) differed among sections of students receiving different instruction. Students from sections in which active-learning techniques were used generally showed slightly higher learning gains as demonstrated by responses to the eight-item abbreviated MCI (unpublished data; K.J. Metzger & P. Kalas, personal communication). Importantly, the proportion of correct responses for each question remained the same regardless of assessment via the entire inventory or via the eight-question subset. Scores on this MCI subset were highly predictive of scores on the entire inventory ($r = 0.88$; Kalas et al., 2013, p. 660). This suggested that abbreviating the inventory did not negatively affect the construct validity of each individual question, although it may decrease the inventory's overall explained variance of meiosis conceptualization.

In our study, the MCI subset of eight items was given as a pre-/post-assessment with no feedback on performance provided to students between assessments. The posttest items were presented on the final exam of the semester, six weeks after the unit of instruction in cell division. Pre-assessment questions were administered as a low-stakes in-class completion activity preceding the mitosis and meiosis pre-class preparation and instruction. Questions were presented to students during class via projected slides, with student responses collected electronically via a quiz on the course's learning management site. Questions and responses were not available to students on the class site. Post-assessment questions were included

in the cumulative final exam, several weeks after instruction, as a more distal capture of student meiosis conceptualization. Following the method used by Kalas et al. (2013), no partial credit was given for "partially correct" responses on items for which the expert response required more than one selected choice (items 4 and 17 in our subset). Cronbach's alpha coefficient was computed as a reliability estimate of internal consistency for the subset of MCI items using both the pretest and posttest responses. To investigate changes in performance, paired t-tests matching individual student pretest and posttest scores were used in analysis of change on average performance across all eight MCI items and also for change in performance on each of the items individually. Independent-samples t-tests were used to test for differences in performance on the MCI between lecture section A and lecture section B. Mean normalized change (c) was also used to investigate the change in performance, calculated as described by Marx and Cummings (2007). Normalized change calculates the mean of the change from pretest to posttest, rather than the change in the mean performance from pretest to posttest. Finally, scores from the unit exam for the unit that included cell division processes were also used as a metric of performance for comparison between the two lecture sections, again using an independent-samples t-test. The unit exam did not contain any items from the MCI.

Multiple regression modeling was used to investigate possible predictive variables: gender, ethnicity, incoming GPA, and comprehensive ACT, with pre-MCI score as the response variable. For multiple regression modeling with post-MCI as the response variable, pre-MCI score was also used as a predictive variable.

In addition to student performance data, we collected data regarding student perceptions of the learning experience in each modeling scenario through two Likert-scale items and two free-response items. The Likert-scale items were "Please rate how strongly you agree with the following statement: Modeling mitosis and meiosis in class helped me understand the processes of cell division" and "Please rate how strongly you agree with the following statement: Modeling mitosis and meiosis in class helped me to understand that genes are physical entities located on chromosomes." The Likert scale used was 1 = strongly agree; 2 = somewhat agree; 3 = not sure; 4 = somewhat disagree; 5 = strongly disagree. The responses to Likert-scaled items for each lecture section were compared using independent t-test analysis. We elected to use parametric statistical tests for the Likert-scaled data following the recommendations of de Winter and Dodou (2010) for five-point Likert scale data analysis.

The free-response item prompts were "If you agreed that modeling mitosis and meiosis in class was beneficial to your learning, please explain in what ways the modeling activity was helpful" and "In what ways do you think the modeling mitosis and meiosis activity is limited, or could be improved?"

Although rigorous analysis of free-response items was not a primary goal of our investigation, we used content analysis to help contextualize Likert-scale responses. To identify emergent themes in student responses to free-response items, content analysis approaches were used. Responses were iteratively read by two reviewers and assigned a theoretical category code (Maxwell, 2008, pp. 236–238). Some responses included reference to more than one theme and were included in more than one reported category.

○ Results

Demographics of Study Population & Lecture Sections

Of 92 students enrolled in the course, 86 consented to participate in the study (participation rate = 93.5%). Of the participants, 78% identified as female and 22% identified as male; 71.18% identified as non-URM (White) and 28.34% identified as a URM (Black, Hispanic, Asian). The mean comprehensive ACT score for the study population was 24, and the mean incoming GPA was 2.87. There were 43 students in each lecture section (N = 43 for lecture section A, N = 43 for lecture section B). There was not a significant difference in gender distribution between lecture sections (two-tailed Fisher's exact test, $p = 0.6040$). Similarly, there was no significant difference with regard to the distribution of students identified as URM between lecture sections (two-tailed Fisher's exact test, $p = 0.1535$).

Incoming Performance Metrics

The distribution of incoming performance metrics (i.e., comprehensive ACT score and entering GPA) was analyzed using independent-samples t-tests. There were no significant differences between the two sections (sections A and B) regarding comprehensive ACT score ($t_{76} = -0.4945$, $p = 0.6224$) or start-of-term college (GPA $t_{84} = -1.72911$, $p = 0.0875$).

Item Reliability – Alpha Coefficient

Using student responses to the pretest MCI, the Cronbach's alpha was 0.1445. Using student responses to the post-assessment MCI results in a Cronbach's alpha of 0.5404.

MCI Pre- & Post-performance

Students improved their performance on the MCI items from pre- to post-assessment. Across both sections, there was a statistically significant increase in performance ($t_{85} = 9.837$, $p < 0.0001$) with an average normalized change of 28.85% on the posttest compared to the pretest. A comparison of performance on the MCI between the two lecture sections revealed no significant differences on the pre-assessment MCI ($t_{84} = -1.32309$, $p = 0.1894$) or post-assessment MCI ($t_{84} = -1.12013$, $p = 0.2659$). Similarly, no significant difference was found when comparing the normalized change (c) between sections ($t_{84} = -0.62974$, $p = 0.5306$).

When performance on the MCI assessment was evaluated for individual items, there was a significant increase in average performance from pre- to post-assessment for items 2, 14, 16, and 17 across the entire study population (Table 2). For item 1, there was evidence of significant decrease in performance from pre- to post-assessment (Table 2). Interestingly, this significant difference was driven by a decrease in performance on this item for section A ($t_{41} = -2.89239$, $p = 0.0061$) but not for section B ($t_{39} = -0.90243$, $p = 0.3724$). Performance for the remaining MCI items (items 4, 13, and 15) showed no significant differences between the pre- and post-assessment. Comparison of performance between lecture sections A and B on the unit exam (which addressed mitosis and meiosis concepts but did not include any MCI items) also showed no significant difference ($t_{84} = -1.50442$, $p = 0.1362$).

Table 2. Summary of Meiosis Concept Inventory (MCI) pre- and post-assessment item means across both sections.

MCI Item	Concept Addressed	Bloom's Level	Pre Score Average	Post Score Average	t Ratio	p	df
1	Ploidy	II	0.50	0.31	2.74955	0.0074**	81
2	Ploidy, what "counts" as a chromosome	III	0.16	0.33	2.99322	0.0037**	81
4	Ploidy	III	0.04	0.05	0.37598	0.7079	81
13	Changes in the amount of DNA in a cell in relation to timing of events in meiosis	II	0.29	0.35	0.896956	0.3724	81
14	Timing of events in the cell cycle and meiosis in relation to chromosomes/ chromatids	I	0.42	0.59	3.093982	0.0027**	81
15	Timing of events (segregation of sister chromatids); consequences of crossing over	II	0.33	0.49	1.834277	0.0703	81
16	Timing of events (segregation of sister chromatids); consequences of crossing over	II	0.23	0.70	7.024216	<0.0001***	81
17	Gamete formation, segregation of alleles and chromosomes	IV	0.341	0.628	4.135866	<0.0001***	81

Notes: A single asterisk (*) indicates significance at the $p < 0.05$ level, two asterisks (**) indicate significance at the $p < 0.01$ level, three asterisks (***) indicate significance at the $p < 0.001$ level. Concept(s) addressed and Bloom's level as reported in Kalas et al. (2013).

Regression Modeling

Multiple regression modeling was completed with predictor variables of gender, ethnicity, comprehensive ACT, college GPA at the start of term, and lecture section (Table 3). In pretest performance, the only variable that was a significant predictor of performance on the MCI subset was ethnicity, with URM students scoring, on average, 12 percentage points lower than non-URM students (non-URM pre-assessment mean score = 27.664, URM pre-assessment mean score = 15.625). The adjusted power for this variable was 0.7134 (Wright & O'Brien, 1988), and the Cohen's f effect size (defined as the square root of μ/μ^2) was 0.333, which is a medium effect (Cohen, 1988).

In the multiple regression for posttest MCI performance, the same predictor variables were used, with the addition of pretest MCI to the model. In that model, college GPA at the start of term and comprehensive ACT were significant predictors of performance (see Table 3), with adjusted power of 0.810 and 0.921, respectively. Cohen's f was 0.359 for ACT and 0.306 for GPA, both of which are a medium effect (Cohen, 1988). In posttest response data, ethnicity was no longer a predictor variable (non-URM post-assessment mean score = 50.717, URM student post-assessment mean score = 41.406).

Student Perceptions of Modeling Activities

Students who participated in the pipe-cleaner version of the modeling exercise (section B) reported a significantly higher agreement with the item "Modeling mitosis and meiosis in class helped me understand the process of cell division" as compared to students who participated in the sock modeling activity ($t_{72} = -2.31788$, $p < 0.023$). Mean agreement was 2.18 for section B, compared to a mean agreement of 2.83 for section A (1 = strongly agree). However, there was no significant difference in student responses to the item "Modeling mitosis and meiosis in class helped me to understand that genes are physical entities located on chromosomes" ($t_{72} = -1.01645$, $p > 0.31$). Mean agreement with this item was 2.54 for section A and 2.23 for section B.

Content analysis of student responses from both sections (summarized in Table 4) indicated a positive response to being able to

Table 3. Multiple regression modeling predicting student pre- and post-assessment MCI scores.

	t	p	B	β	F	df	p	R^2
MCI Pre								
Overall model					2.799	76	0.023	0.165
Gender (F)	−0.94	0.349	−2.195	−0.106				
Ethnicity (URM)	**−2.79**	**0.007**	**−5.803**	**−0.313**				
ACT	0.85	0.396	0.528	0.106				
GPA	0.59	0.85	2.289	0.074				
Lecture section (A)	0.50	0.619	0.945	0.056				
MCI Post								
Overall model					8.433	76	<0.0001	0.420
Gender (F)	−0.63	0.053	−0.120	−0.060				
Ethnicity (URM)	−0.17	0.865	−0.030	−0.017				
ACT	**3.61**	**0.0006**	**0.181**	**0.378**				
GPA	**3.09**	**0.0029**	**0.967**	**0.327**				
Lecture section (A)	0.74	0.463	0.113	0.070				
MCI pre score	0.93	0.353	0.112	0.093				

Notes: Significant predictors are in bold. Ethnicity was coded as under-represented minority (URM) or non-URM. ACT is comprehensive ACT score. GPA is the student's university GPA at the beginning of the term (spring semester, first year). Lecture section was coded as A (sock modeling) or B (pipe-cleaner modeling).

physically represent the processes of mitosis and meiosis, whether with pipe cleaners or socks. In particular, student responses from both sections suggested that the use of small craft beads to represent physical genetic loci was an especially effective approach in solidifying student understanding of genes as physical entities with a fixed location. Further, the use of different colored beads to represent different alleles at a single locus in a heterozygous individual was especially helpful in being able to demonstrate the outcomes of crossing over during meiosis I. When students were asked how the modeling exercise could be improved, students in lecture section A (sock modeling) suggested more explanation and instructor guidance accompanying the modeling activity to reduce confusion much more frequently than students in lecture section B (pipe-cleaner modeling) (Table 4).

○ Discussion

In this study, two active-learning approaches involving modeling were assessed and compared for their effectiveness in supporting student learning of the cellular division processes of mitosis and meiosis. Using a subset of the validated MCI as a pretest and post-test instrument, we found that regardless of the active-learning modeling approach used during instruction, students demonstrated significant learning gains pre- to post-assessment. This result is consistent with other studies that demonstrate significant learning gains following instruction. Although Kalas et al. (2013) report Bloom's taxonomy levels for MCI items, too few items were included in our study to robustly determine whether students performed differently on MCI items of different cognitive levels. The greatest learning gains occurred for MCI items 16 and 17, which both address segregation of alleles. Cronbach's alpha for the pre-assessment was quite low, indicating a high degree of randomness in student responses. The Cronbach's alpha for the post-assessment increased to 0.5404, indicating greater internal consistency among student responses on the posttest. While lower than the 0.78 reported by Kalas et al. (2013, p. 659) for the entire concept inventory, we used only a subset of the MCI in our assessments. Additionally, multiple concepts were represented in the items that comprised the subset used here, which could contribute to the lower alpha we observed.

No significant differences in student performance were found between treatment groups in posttesting as determined through t-test and multiple regression analysis. Multiple regression analysis of pre-assessment responses revealed ethnicity to be a significant predictor of performance on the pre-assessment. In contrast, no

Table 4. Qualitative analysis of student responses regarding the helpfulness and limitations of the modeling activities.

Prompt & Total Number of Student Responses (Section A; Section B)	Theme	Percentage of Student Responses in Theme: Total (Section A, Section B)	Example Student Response
"If you agreed that modeling mitosis and meiosis in class was beneficial to your learning, please explain in what ways the modeling activity was helpful." N = 69 (38; 31)	Visual representation	49.3% (44.74%, 54.84%)	"Visualizing the alleles and how they actually switched over. As well as realizing that they duplicate then proceed with the meiosis or mitosis."
	Physical manipulation	28.99% (26.32%, 32.26%)	"I love having a physical component to the ideas we talk about in class. I can memorize what you say in a lecture but I actually learn what happens when it is physically happening."
	Compare mitosis and meiosis	14.50% (18.42%, 9.68%)	"It was helpful in showing how the chromosomes line up compared to meiosis and mitosis, as well as some of the phases."
	Physical nature of genetic loci and exchange of genetic information	14.50% (18.42%, 9.68%)	"The beads helped me to understand that genes are located on the chromosomes and that they are exchanged during crossing over."
"In what ways do you think the modeling mitosis and meiosis activity is limited, or could be improved?" N = 74 (48, 31)	Instructions introduced confusion	40.54% (58.14%, 16.12%)	"The directions were confusing to follow, and waiting around to figure out what was going on made me more confused. I would recommend being more clear about the parental and maternal strand, and emphasizing that one bead goes on each pin for each sock."
	Additional instructor explanation	16.22% (23.26%, 6.45%)	"I think it could be helpful if we went over this activity as a class first so that we knew what was supposed to be happening, and then did the activity as small groups to get a better understanding."
	Large-group activity	9.46% (16.28%, 0%)	"I think it should have been done in one big group, and then the rest of the class watched it. I feel like it would have been easier to have [the instructor] explain everything while it was going on, too."

significant difference was found between the average post-assessment performance of URM students compared with that of non-URM students. This result suggests that the instruction that occurred between the pre- and post-assessment may have disproportionately and positively affected URM students, which resulted in reduction of the performance gap that existed between URM and non-URM students prior to instruction. In post-assessment regression modeling, only comprehensive ACT score and college GPA at the beginning of term emerged as predictive variables of post-assessment performance. These variables were not significant predictors on the pre-assessment. This result indicates that students with stronger incoming academic performance metrics outperform their relatively academically less successful peers, regardless of the instructional approach used.

Given that the two treatment groups in this study were well matched with regard to sample size, incoming performance metrics, and known demographics, we conclude that both modeling exercises were equally effective in supporting student learning. Since there is no difference in performance due to instruction, the selection of the modeling activity used to support student learning can be made on the basis of other criteria, such as instructor preference, physical classroom layout, or available supplies. While our pretest and posttest assessments were separated by several weeks, our study is limited in that we were not able to assess whether the learning gains persisted over a longer period (i.e., a semester or more after instruction). Therefore, we cannot eliminate the possibility that one of these approaches may result in greater longitudinal retention.

While the performance data did not support a difference in learning gains between the two instructional approaches implemented, the Likert-scale student perception data we collected indicated a significant difference in student-perceived helpfulness: students who participated in the pipe-cleaner modeling (section B) indicated higher agreement with the statement "Modeling mitosis and meiosis in class helped me understand the process of cell division" as compared to students who experienced the sock modeling (section A). Content analysis of student responses to free-response items suggest that the modeling activity using socks would benefit from additional structure, as students in section A more frequently cited being confused by the instructions for the modeling activity and also more frequently reported a desire to perform the modeling as a class demonstration rather than in small groups. Because our study included only one semester of data, the greater perceived helpfulness of the pipe-cleaner modeling, while significant, may not be generalizable.

In conclusion, this study provides evidence of the equal effectiveness of two active-learning approaches to the teaching of mitosis and meiosis. As such, our findings support flexibility for individual instructors to determine which active-learning approach is the best fit for their class and their learners. However, in spite of concentrated effort to focus instruction on improved understanding of meiosis, student misconceptions still persisted after instruction, as evidenced by student responses to items on the post-assessment MCI, especially item 1. Hence, although students improved in their knowledge of meiosis from the instructional activities described in our study, students may require multiple exposures to focused learning opportunities to fully ameliorate misconceptions regarding this complex, yet pedagogically crucial, cellular process. Future research questions of interest are to investigate (1) whether the significant difference in perceived helpfulness of the modeling approaches is consistent in a subsequent offering of the same course (or other populations of students); and (2) whether combining the two modeling approaches in one population of students would result in greater learning gains than what we observed from either of the modeling approaches applied singly.

○ Acknowledgments

This research has been supported by tenure-track faculty start-up funds provided to K.J.M. by the University of Minnesota Rochester. J.Y.Y.'s collaboration was supported by a Career Development Internship during her Ph.D. studies at Mayo Graduate School in Rochester, MN. The authors have no conflicts of interest to report. There is no connection between any authors and a commercial product being used or included in the manuscript.

References

Angelo, T.A. & Cross, K.P. (1993). *Classroom Assessment Techniques, 2nd ed*. San Francisco, CA: Jossey-Bass.

Beichner, R.J., Saul, J.M., Abbott, D.S., Morse, J.J., Deardorff, D.L., Rhett, J.A., et al. (2007). The Student-Centered Activities for Large Enrollment Undergraduate Programs (SCALE-UP) project. In E.F. Redish & P.J. Cooney (Eds.), *Research-Based Reform of University Physics*. College Park, MD: American Association of Physics Teachers.

Chinnici, J.P., Neth, S.Z. & Sherman, L.R. (2006). Using "chromosomal socks" to demonstrate ploidy in mitosis & meiosis. *American Biology Teacher*, *68*, 106–109.

Chinnici, J.P., Yue, J.W. & Torres, K.M. (2004). Student as "human chromosomes" in role-playing mitosis and meiosis. *American Biology Teacher*, *66*, 35–39.

Clark, D.C. & Mathis, P.M. (2000). Modeling mitosis and meiosis. *American Biology Teacher*, *62*, 204–206.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences, 2nd ed*. Hillsdale, NJ: Erlbaum.

Coleman, D. (1986). A simple model for use in teaching cell division and genetics. *Journal of Biological Education*, *20*, 158–159.

de Winter, J.C.F. & Dodou, D. (2010). Five-point Likert items: *t* test versus Mann-Whitney-Wilcoxon. *Practical Assessment, Research & Evaluation*, *15*, 1–16.

Dori, Y.J. & Belcher, J. (2005). How does technology-enabled active learning affect undergraduate students' understanding of electromagnetism concepts? *Journal of the Learning Sciences*, *14*, 243–279.

Dori, Y.J., Hult, E., Breslow, L. & Belcher, J.W. (2007). How much have they retained? Making unseen concepts seen in a freshman electromagnetism course at MIT. *Journal of Science Education and Technology*, *16*, 299–323.

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H. & Wenderoth, M.P. (2015). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences USA*, *111*, 8410–8415.

Harrell, P.E. (2001). How a dragon gets its wings. *Science Teacher*, *68*, 52–57.

Kalas, P., O'Neill, A., Pollock, C. & Birol, G. (2013). Development of a meiosis concept inventory. *CBE–Life Science Education*, *12*, 655–644.

Kara, Y. & Yesilyurt, S. (2007). Comparing the impacts of tutorial and edutainment software programs on students' achievements, misconceptions, and attitudes towards biology. *Journal of Science Education and Technology*, *7*, 32–41.

Kargöz, M. & Çakir, M. (2011). Problem solving in genetics: conceptual and procedural difficulties. *Educational Sciences: Theory and Practice*, *11*, 1668–1674.

Kindfield, A.C.H. (1991). Confusing chromosome number and structure: a common student error. *Journal of Biological Education* 25:193–200.

Kindfield, A.C.H. (1993). Biology diagrams: tools to think with. *Journal of the Learning Sciences*, *3*, 1–36.

Kindfield, A.C.H. (1994). Understanding a basic biological process: expert and novice models of meiosis. *Science Education*, *78*, 255–283.

Kreiser, B. & Hairston, R. (2007). Dance of the chromosomes: a kinetic learning approach to mitosis and meiosis. *Bioscene*, *33*, 6–10.

Levy, F. & Benner, D.B. (1995). Using ribbon models of chromosome modifications to explore the process of meiosis. *American Biology Teacher*, *57*, 532–535.

Lewis, J., Leach, J. & Wood-Robinson, C. (2000a). All in the genes? Young people's understanding of the nature of genes. *Journal of Biological Education*, *34*, 74–79.

Lewis, J., Leach, J. & Wood-Robinson, C. (2000b). Chromosomes: the missing link - young people's understanding of mitosis, meiosis, and fertilization. *Journal of Biological Education*, *34*, 189–199.

Lewis, J., Leach, J. & Wood-Robinson, C. (2000c). What's in a cell? Young people's understanding of the genetic relationship between cells, within an individual. *Journal of Biological Education*, *34*, 129–132.

Lock, J. & McDermid, H.E. (2005). Using pool noodles to teach mitosis and meiosis. *Genetics*, *170*, 5–6.

Luo, P. (2012). Creating a double-spring model to teach chromosome movement during mitosis & meiosis. *American Biology Teacher*, *74*, 266–269.

Marx, J.D. & Cummings, K. (2007). Normalized change. *American Journal of Physics*, *75*, 87–91.

Mathis, P.M. (1979). The use of manipulative models in teaching mitosis and meiosis. *American Biology Teacher*, *9*, 558–559, 561.

Maxwell, J.A. (2008). Designing a qualitative study. In L. Bickman & D.J. Rog (Eds.), *The Handbook of Applied Social Research Methods, 2nd ed*. (pp. 214–253). Thousand Oaks, CA: Sage.

McKean, H.R. & Gibson, L.S. (1989). Hands-on activities that relate mendelian genetics to cell division. *American Biology Teacher*, *51*, 294–299.

Mertens, T.R. & Walker, J.O. (1992). A paper-&-pencil strategy for teaching mitosis & meiosis, diagnosing learning problems & predicting examination performance. *American Biology Teacher*, *54*, 470–474

Mézard, C., Jahns, M.T. & Grelon M. (2015). Where to cross? New insights into the location of meiotic crossovers. *Trends in Genetics*, *31*, 393–401.

Newman, D.L., Catavero, C.M. & Wright, L.K. (2012). Students fail to transfer knowledge of chromosome structure to topics pertaining to cell division. *CBE–Life Sciences Education*, *11*, 425–436.

Oakley, C.R. (1994). Using sweat socks & chromosomes to illustrate nuclear division. *American Biology Teacher*, *56*, 238–239.

Ozcan, T., Yildirim, O. & Ozgur, S. (2012). Determining of the university freshman students' misconceptions and alternative conceptions about mitosis and meiosis. *Procedia–Social and Behavioral Sciences*, *46*, 3677–3680.

Öztap, H., Özay, E. & Öztap, F. (2003). Teaching cell division to secondary school students: an investigation of difficulties experienced by Turkish teachers. *Journal of Biological Education*, *38*, 13–15.

Page, S. & Hawley, S. (2003). Chromosome choreography: the meiotic ballet. *Science*, *301*, 785–789.

Page, S. & Hawley, S. (2004). The genetics and molecular biology of the synaptonemal complex. *Annual Review of Cell and Developmental Biology*, *20*, 525–558.

Quinn, F., Pegg, J. & Panizzon, D. (2009). First-year biology students' understandings of meiosis: an investigation using a structural theoretical framework. *International Journal of Science Education*, *31*, 1279–1305.

Smith, M.U. (1991). Teaching cell division: student difficulties and teaching recommendations. *Journal of College Science Teaching*, *21*, 28–33.

Stavroulakis, A.M. (2005). Meio-socks & other genetic yarns. *American Biology Teacher*, *67*, 233–238.

Stencel, J. (1995). A string & paper game of meiosis that promotes thinking. *American Biology Teacher*, *57*, 42–45.

Stewart, J. (1982). Difficulties experienced by high school students when learning basic Mendelian genetics. *American Biology Teacher*, *44*, 80–82,84,89.

Stewart, J. (1983). Student problem solving in high school genetics. *Science Education*, *64*, 523–540.

Stewart, J., Hafner, B. & Dale, M. (1990). Students' alternate views of meiosis. *American Biology Teacher*, *55*, 228–232.

Walker, J.D., Brooker, D.C. & Baepler, P. (2011). Pedagogy and space: empirical research on new learning environments. *EDUCAUSE Quarterly*, *34*. http://er.educause.edu/articles/2011/12/pedagogy-and-space-empirical-research-on-new-learning-environments.

Williams, M., Haydel Debarger, A., Montgomery, B.L., Zhou, X. & Tate E. (2011). Exploring middle school students' conceptions of the relationship between genetic inheritance and cell division. *Science Education*, *96*, 78–103.

Wright, L.K. & Newman, D.L. (2011). An interactive modeling lesson increases students' understanding of ploidy during meiosis. *Biochemistry and Molecular Biology Education*, *39*, 344–351.

Wright, S. & O'Brien, R.G. (1988). Power analysis in an enhanced GLM procedure: what it might look like. In *Proceedings of the Thirteenth Annual SAS Users Group International Conference* (pp. 1097–1102). Cary, NC: SAS Institute.

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Appendix 1.

Sock Mitosis and Meiosis Modeling Activity
Adapted from Wright and Newman, 2011 (1).

Instructor Preparation/Modifications to Wright et al, 2011 for implementation at UMR:

Instructions will include directive to model mitosis as well as meiosis

All students will participate in modeling, rather than only 6 students acting as chromosomes with socks and 2 students acting as centrosomes (8 students total). Rather, we will utilize 4 groups of students, all modeling. We will use N=4, 2N=8 to involve all students. This will affect the correct responses for items in Wright et al., 2011 table II.

1. Instructor will divide students into 4 groups of 11 students each. There will not be parity among males and females (as male students are outnumbered by female students). For each group, 8 students will be given the number 1-4 to represent different chromosomes in the hypothetical genome. Two students with the same number will act as homologous pairs of chromosomes. Two students in each group of 11 will be assigned the role of centrosomes (C). The final student in each group of 11 will serve as the "Reader" and will read the instructions to the group members.
2. Each student with a number 1-4 is given a unique solid-colored sock (with its mate hidden inside) in one of four sizes (adult large, adult small, child, and infant). Students will be directed by their group's Reader to hold up the sock in one hand. Student volunteers will then "replicate" their DNA by pulling the hidden sock out and will then be instructed to hold both socks in the same hand. Pins with colored beads will be used to represent alleles. Maternal and paternal alleles will be represented by different colored beads for the same gene. Students will be asked to pin a bead of the same color as the parental sock on the newly replicated sock.
3. Students will count the number of chromosomes present in the hypothetical cell.

Instructions here will diverge depending on if students are modeling mitosis or meiosis.

4. For mitosis, students will be asked to form alignment along the metaphase plate. The 2 students role playing centrosomes will "rope" the sister chromatids and pull them apart to opposite poles of the cell. Students will count how many chromosomes are present in the daughter cells.

End Mitosis role playing

For meiosis, Student "chromosomes" are then asked by the "Reader" to find their homologous pair.

5. Students will be asked to participate in crossing over between the two homologous chromosomes, involving only one chromatid from each replicated homologous chromosome. Specifically, the "Reader" for the group will instruct students representing homologous chromosomes to link arms to represent the formation of a synaptonemal complex, and perform an exchange of genetic material represented by the beads pinned on the socks.
6. The "Reader" will instruct homologous pairs of chromosomes to align along the metaphase plate. The 2 students role playing centrosomes will "rope" the homologous chromosomes and pull them apart to opposite poles of the cell. Students will be asked to count the number of chromosomes present in each daughter cell, and whether the daughter cells are diploid or haploid.
7. Individual students representing replicated chromosomes (sister chromatids) with 2 socks being held in one hand will be instructed to align along metaphase plate for meiosis II division.

End meiosis role playing

1. Wright LK, Newman DL. 2011. An interactive modeling lesson increases students' understanding of ploidy during meiosis. Biochem Mol Biol Educ 39:344–351.

Modeling Mitosis and Meiosis: Reader Handout

A. Mitosis Modeling

1. Before you begin modeling, consider a diploid organism that has four chromosomes, numbered 1, 2, 3, 4. What is a normal karyotype for a **somatic cell** of this organism?
2. Students in your group either have a chromosome number or a "C." Students with a chromosome number will need to find their appropriately sized sock (*remember, chromosomes are numbered from largest to smallest*). Students who are assigned a "C" are acting as the centrosomes and will each need a length of yarn.
3. Students who are assigned a chromosome: Hold up your sock in one hand.
4. "Replicate" your DNA chromosome by pulling the hidden sock out and then hold both socks in the same hand. Pins with colored beads will be used to represent alleles. Maternal and paternal alleles will be represented by different colored beads for the same gene. Pin a bead of the same color as the parental sock on the original and newly replicated socks according to the genotype information below:

i. On chromosome 1 reside genes A and B:

Gene A alleles: black/white (black is dominant to white)

Gene B alleles: dark blue/light blue (dark blue is dominant to light blue)
Genotype: Your organism is heterozygous for gene A and heterozygous for gene B. Assume the maternal copy of chromosome 1 has dominant alleles for both genes.

ii. On chromosome 2 reside genes C and D.

Gene C alleles: green/yellow (alleles have codominant relationship)
Gene D: Red (This gene is monomorphic: it only comes in one form!)
Genotype: Your organism is heterozygous for gene C, homozygous for gene D.

iii. On chromosome 3 resides gene E
Gene E alleles: pink/purple (Pink is dominant to purple)
Genotype: Your organism is homozygous for the recessive allele

5. As a group, count the number of chromosomes present in the hypothetical cell.
6. Form alignment along the metaphase plate. How are the replicated chromosomes (sister chromatids) aligned?
7. The 2 students role playing centrosomes will "rope" the sister chromatids and pull them apart to opposite poles of the cell.
8. As a group, count how many chromosomes are present in the daughter cells.

End Mitosis role playing

B. Meiosis Modeling

1. Before you begin modeling, consider a diploid organism that has four chromosomes, numbered 1, 2, 3, 4. What is a normal karyotype for a **somatic cell** of this organism?
2. "Replicate" your DNA chromosome by pulling the hidden sock out and then hold both socks in the same hand. Pins with colored beads will be used to represent alleles. *(This will be the same as above, you do not need to pin again)*
3. Pairs of homologous chromosomes will need to form a tetrad (or bivalent) to participate in crossing over (also known as homologous recombination). Students holding replicated chromosome 1s will indicate the formation of a bivalent by linking arms.
4. Perform crossing over for one of the genes on chromosomes 1 and 2.
5. Are there any new allele combinations present after recombination that were not present before recombination? Explain.
6. What does alignment look like for metaphase of meiosis I?
7. Complete meiosis I by having student centrosomes separate bivalents (paternal and maternal homologous chromosomes) to 2 daughter cells.
8. As a group, count the number of chromosomes present in the hypothetical cell.
9. Complete meiosis II by having student centrosomes separate sister chromatids to daughter cells.
10. As a group, count the number of chromosomes present in the hypothetical cell.

End Meiosis role playing

Appendix 2.

Modeling Mitosis and Meiosis

A. Modeling Karyotypes and Genotypes

1. Consider a diploid organism that has four chromosomes, numbered 1, 2, 3, 4. What is a normal karyotype for a **somatic cell** of this organism? To begin, model a normal karyotype of a somatic cell with the appropriate pipe cleaners.
2. Placing genes on chromosomes:

a On chromosome 1 reside genes A and B.

i. Gene A alleles: black/white (black is dominant to white)

ii. Gene B alleles: dark blue/light blue (dark blue is dominant to light blue)

Genotype: Your organism is heterozygous for gene A and heterozygous for gene B. Assume the maternal copy of chromosome 1 has dominant alleles for both genes.

b On chromosome 2 reside genes C and D.

i. Gene C alleles: green/yellow (alleles have codominant relationship)

ii. Gene D: Red (This gene is monomorphic: it only comes in one form!)

Genotype: Your organism is heterozygous for gene C, homozygous for gene D.

c On chromosome 3 resides gene E

i. Gene E alleles: pink/purple (Pink is dominant to purple)

Genotype: Your organism is homozygous for the recessive allele

B. Modeling Mitosis and Meiosis

For #4, each person should select ***one pair of homologous chromosomes.***

4. Model mitosis with your materials. What do the chromosomes look like in metaphase?

Share your answers for #4 in your group.

For # 5, work in pairs to model meiosis for ***either chromosome 1 or chromosome 2.***

5. Model meiosis with your materials. What are possible outcomes of crossing over for each gene? What do the chromosomes look like in Anaphase I? Metaphase II?

Share your answers for #5 in your group.

Appendix 3.

Mitosis and Meiosis Discussion Questions

1. What are homologues, sister chromatids, and bivalents? When do sister chromatids separate during mitosis? When do sister chromatids separate during meiosis?

2. Describe the arrangement of chromosomes at metaphase of mitosis. How is this different from the arrangement of chromosomes at metaphase I of meiosis I?

3. What are the differences in the cells produced by mitosis and meiosis?

Mitosis vs. Meiosis Defining Features Matrix: Complete the following table with information about the listed feature in mitosis and meiosis.

Feature	Mitosis	Meiosis I	Meiosis II
Preceded by DNA replication? (Yes/No)			
When is formation of bivalents?			
Crossing over during prophase? (Yes/No)			
Describe alignment at metaphase plate			
Describe separation at anaphase			
Genetically identical daughter cells produced? (Yes/No)			
Haploid daughter cells produced? (Yes/No)			