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The Efficacy of Student-Centered Instruction in Supporting Science Learning

E. M. Granger *et al.*

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tally demonstrated that slip acceleration quickens fault weakening, and, in light of the transient nature of earthquake slip (*1–3*), we propose that slip acceleration controls seismic weakening in addition to slip distance and slip velocity.

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Supplementary Materials

www.sciencemag.org/cgi/content/full/338/6103/101/DC1
Materials and Methods
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The Efficacy of Student-Centered Instruction in Supporting Science Learning

E. M. Granger,[1]* T. H. Bevis,[1] Y. Saka,[2] S. A. Southerland,[3] V. Sampson,[3] R. L. Tate[4]

Transforming science learning through student-centered instruction that engages students in a variety of scientific practices is central to national science-teaching reform efforts. Our study employed a large-scale, randomized-cluster experimental design to compare the effects of student-centered and teacher-centered approaches on elementary school students' understanding of space-science concepts. Data included measures of student characteristics and learning and teacher characteristics and fidelity to the instructional approach. Results reveal that learning outcomes were higher for students enrolled in classrooms engaging in scientific practices through a student-centered approach; two moderators were identified. A statistical search for potential causal mechanisms for the observed outcomes uncovered two potential mediators: students' understanding of models and evidence and the self-efficacy of teachers.

The need for a different approach to science teaching and learning has been the focus of several recent policy and economic reports (*1*, *2*). Research as synthesized by the National Research Council suggests that the goal of science instruction should be to help students develop four aspects of scientific proficiency, the ability to (i) know, use, and interpret scientific explanations of the natural world; (ii) generate and evaluate scientific evidence and explanations; (iii) understand the nature and development of scientific knowledge; and (iv) participate productively in scientific practices and discourse (*3–5*). This approach to science teaching will require a shift from the teacher-centered instruction common in science classrooms to more student-centered methods of instruction. The defining feature of these instructional methods is who is doing the sense-making. In teacher-centered instruction, the sense-making is accomplished by the teacher and transmitted to students through lecture, textbooks, and confirmatory activities in which each step is specified by the teacher. In these classrooms, the instructional goal is to help students know scientific explanations, which is only part of the first aspect of scientific proficiency. In student-centered instruction, the sense-making rests with students, and the teacher acts as a facilitator to support the learning as students engage in scientific practices (*3*).

The effectiveness of student-centered instruction in helping students develop scientific proficiency is supported by a number of largely small-scale, narrowly focused studies (*3*, *5*). Despite accumulating support for a student-centered approach, few large-scale studies have evaluated the effectiveness of such instruction, and their results, taken as a whole, are contradictory and inconclusive (*6–13*). The same is true of only randomized-cluster or quasi-randomized studies examined separately (*6*, *11*, *14*, *15*). Many factors may contribute to the varied results, because tightly controlling potentially influential variables is difficult in classroom settings. One central factor is that the comparison condition (i.e., control group) is often "undefined or assumed to be 'traditional'" (*14*). Likewise, possible "contamination of the untreated teachers" and cases where investigators did not "vigorously guard" against special resource materials may have influenced results (*13*). Indeed, many studies described in the literature do not discuss how fidelity to the curriculum or instructional approach was measured or whether it was assessed.

We therefore compared the effectiveness of student-centered with teacher-centered instruction using a randomized-cluster experimental design, intended to control as many variables as possible given the inherent differences between the two instructional approaches. Specifically, the effectiveness of the student-centered Great Explorations in Math and Science Space Science Curriculum Sequence (SSCS) (*16*) and professional development of teachers focused on these materials (treatment group) was compared with that of a teacher-centered curriculum (district-adopted textbook) enacted with a teacher-centered approach (control group). For details of each curriculum, teacher professional development, and instructional approach, see the supplementary materials. Mindful of limits on securing meaningful data imposed by testing the age group for whom SSCS is appropriate (fourth and fifth grades), we selected four student outcomes aligned with the four aspects of scientific proficiency for this research: space science content knowledge, knowledge about models and evidence in science, views of scientific inquiry, and attitude toward science. The research was designed to (i) compare the effectiveness of the two instructional approaches in supporting elementary students' science learning; (ii) identify teacher characteristics (teacher moderating variables) that might influence the learning; (iii) identify those for whom this instructional approach might work (student moderating variables); and (iv) identify how the treatment might indirectly affect student outcomes (mediating variables).

[1]Office of Science Teaching Activities, Florida State University, Tallahassee, FL 32306–4295, USA. [2]Bülent Ecevit Üniversitesi Ereğli Eğitim Fakültesi, Turkey. [3]FSU-Teach/School of Teacher Education, Florida State University, Tallahassee, FL 32306–4459, USA. [4]Educational Evaluation and Research, Florida State University (retired), 415 Castleton Circle, Tallahassee, FL 32312, USA.

*To whom correspondence should be addressed: E-mail: granger@bio.fsu.edu

Data were collected from 125 fourth- and fifth-grade classrooms. Randomization occurred at the level of assignment of teachers to treatment or control group; control and treatment groups were matched according to grade level, socioeconomic status (SES), school statewide assessment performance, and student ethnic diversity. Student demographics were collected (table S1). Contexts included urban, suburban, and rural and high- and low-SES schools; 2594 students participated—1418 in the classrooms of 66 treatment teachers and 1176 in the classrooms of 59 control teachers (for details, see the supplementary materials). Student conceptual development and affective dimensions were assessed by means of four instruments: (i) Space Science Content Test (*17*); (ii) Homerton Science Attitudes Survey (*18*); (iii) Models and Evidence Questionnaire (*19*); (iv) Views of Scientific Inquiry (VOSI) Elementary Version Questionnaire (*20*). Both groups were assessed immediately before the unit, immediately after the unit, and 5 months ± 2 weeks after the unit (see the supplementary materials for test and scoring details). Each teacher's fidelity to the assigned teaching approach was assessed with the Reformed Teacher Observation Protocol (RTOP) (*21*) two to three times during the unit. RTOP is a measure of the degree to which lesson enactment is aligned with student-centered science instruction. To help identify potential teacher moderators, we also assessed teachers' space-science content knowledge, science attitudes, views of scientific inquiry, self-efficacy, and beliefs about science teaching before and after their participation in the project.

Multilevel (hierarchical linear) modeling was used to estimate the SSCS's effects with moderation and to account for interdependencies of student outcomes within teachers (*22*, *23*). Each student outcome was reflected in two measures, the postmeasure and delayed postmeasure. Potential explanatory variables for each outcome included (i) pretest measure; (ii) treatment variable (SSCS or control); (iii) teacher cohort (year 1 or 2); (iv) grade level (4 or 5); (v) interactions among the treatment, cohort, and grade variables; (vi) teacher years of experience; (vii) preassessments of teacher outcomes; (viii) student ethnicity; (ix) student SES, based on participation in the free or reduced lunch program (FRL); (x) student gender; and (xi) primary language of the student. Inspection of bivariate correlations and backward elimination processes produced the final models. Special attention was given to the possibility of interactions involving student and teacher moderators. Multilevel mediation models addressed the question of how the treatment might indirectly affect student outcomes (mediating variables) by two analytic approaches: an application of multilevel modeling based on separate models for each of the variables explained by the model and a simultaneous solution by multilevel path analysis (*24*). Positive mediation results should be considered as evidence that the data are consistent with the hypothesized mediation. To compare effect sizes for outcomes with different scales, we also present effects in standardized form [0.2 is small, 0.5 medium, and 0.8 large (*25*)] but note that a small effect should not be interpreted as trivial (*15*, *25*). The VOSI outcome could not be similarly standardized, because it is an ordered binary variable with two levels. For VOSI, a nonlinear version of multilevel modeling describes effects as an odds ratio (i.e., the odds of SSCS students giving a response coded as "transitional/informed" rather than "naïve" divided by the odds of control students doing so); a ratio of 1.1 is at the threshold of practical importance. (See the supplementary materials for details of statistical analysis.)

Average RTOP scores for SSCS teachers were 27.3 points (out of 100) higher than those of control teachers, a statistically significant difference (P = 0.001); groups overlapped only modestly, indicating that the two instructional approaches were implemented with fidelity. To examine within-group RTOP effects, we transformed total RTOP scores to within-group deviation scores. For each student outcome for which the SSCS effect was statistically significant (content knowledge, models and evidence, and VOSI) (see Table 1), the effect of the RTOP deviation score was positive and statistically significant (P = 0.002 to 0.017). That is, after the SSCS treatment effect was controlled for, the RTOP deviation score could be considered as a "dosage" variable within each group resulting in an increase in student outcomes. This finding suggests that student engagement in

Table 1. SSCS total effects for student outcomes. OR, odds ratio.

Outcome	Unstandardized effect	P	Standardized effect†
	Posttest outcome		
Content knowledge‡	0.488*	0.002	0.171*
VOSI§	0.464*	0.002	OR = 1.59
Models and evidence			
No FRL	0.354*	<0.001	0.682*
FRL	0.261*	<0.001	0.503*
Attitude toward science	0.009	0.753	0.014
	Delayed posttest outcome		
Content knowledge‡	0.187	0.193	0.067
VOSI‖	0.333*	0.015	OR = 1.40
Models and evidence	0.285*	<0.001	0.573*
Attitude toward science	0.020	0.530	0.029

*Statistically significant, with a family-wise error rate of 0.10 (i.e., for a test family of four post-outcomes or four delayed post-outcomes, $P < 0.10/4 = 0.025$). †For all outcomes except VOSI, standardized effects were obtained by division of raw-score SSCS coefficients by the outcome standard deviations. ‡Results are from a sample from which one extreme outlier was removed. ‖The student variable of VOSI is dichotomous. The associated unstandardized SSCS effect is the SSCS coefficient in a model for the log odds (logit) of the outcome, and the standardized SSCS effect is the OR for the transitional/informed outcome.

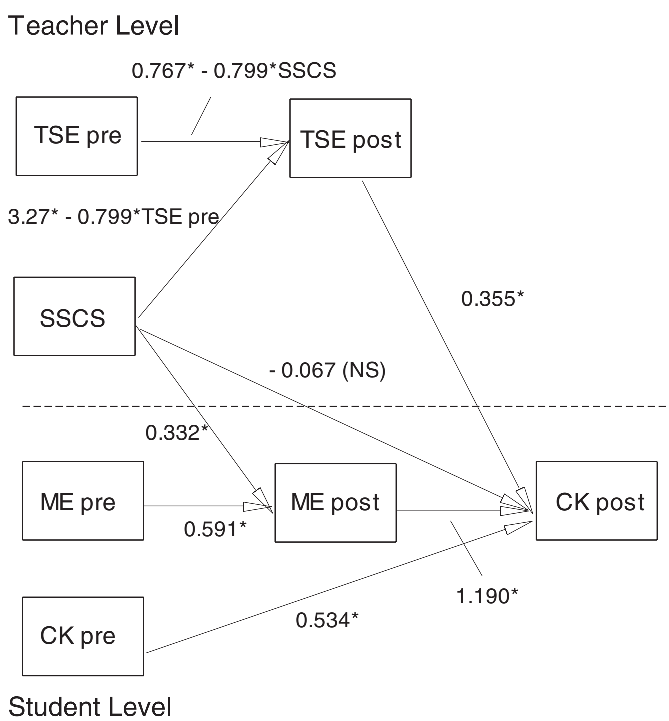

Fig. 1. Mediation model for student posttest content knowledge, with path coefficients indicated. *, significant at the 0.05 level; NS, not significant; TSE pre, teacher pretest self-efficacy; TSE post, teacher posttest self-efficacy; ME pre, student pretest models and evidence; ME post, student posttest models and evidence; CK pre, pretest student content knowledge; CK post, posttest student content knowledge.

learning (student-centeredness), as indicated by RTOP scores, is a feature of more effective teaching.

Table 1 summarizes estimated total effects of the SSCS curriculum on student post- and delayed posttest outcomes, including student-level moderators. When a family-wise error rate of 0.10 was controlled for, students in the SSCS group scored significantly higher than control students on content-knowledge, models-and-evidence, and VOSI posttest outcomes. For delayed posttests, the SSCS group remained significantly higher for VOSI and models and evidence. For content-knowledge and models-and-evidence outcomes, the standardized effect magnitudes were ~0.2 and 0.7, respectively. The odds ratio representing the SSCS effect for the VOSI outcome was 1.59; that is, the odds of SSCS students giving transitional/informed responses were 1.59 times greater than those for control students. Interpreting the results of the content-knowledge delayed posttest requires accounting for factors potentially affecting it; foremost is the timing, which placed these assessments within about 2 weeks of statewide assessments and all their concomitant drill and practice in both treatment and control classrooms. The large size (*25*) and persistence of the models-and-evidence and VOSI outcomes are notable.

Only one student characteristic, SES, moderated the SSCS effect on one posttest outcome, models and evidence (Table 1). Although the two SES groups differed in achievement, both high- and low-SES students in the treatment group performed better than did students in the control group. This difference between the groups in the SES achievement gap disappeared by delayed posttesting. This result is consistent with a wide body of research that indicates that students from low-SES groups initially need more support to participate in the practices of science (here, using models and evidence) (*6*, *11*, *26*).

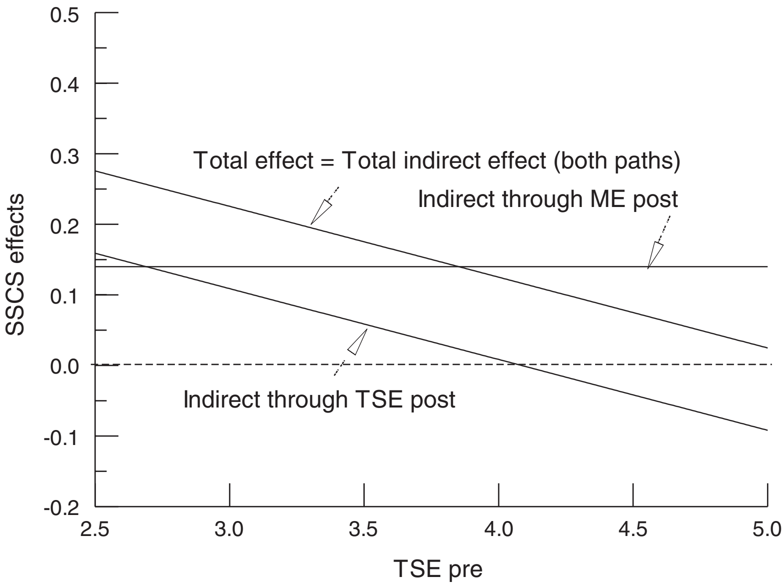

Fig. 2. Standardized effects of SSCS on the student posttest content knowledge outcome. Abbreviations as in Fig. 1.

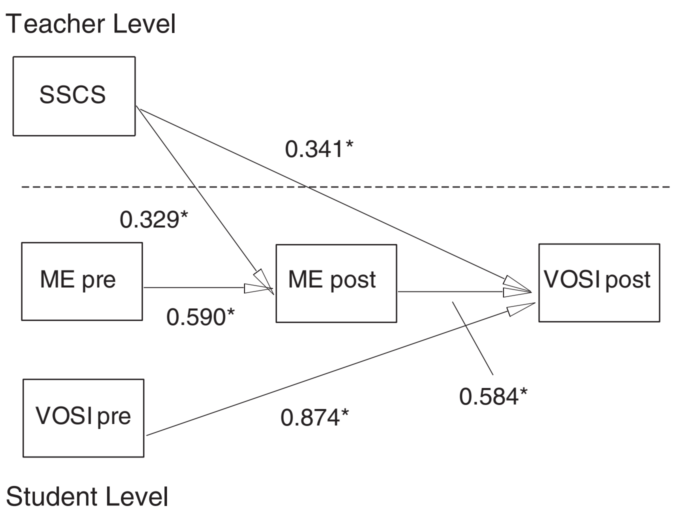

Fig. 3. Mediation model for posttest VOSI, with path coefficients indicated. Model is for the log odds (logit) of student posttest VOSI. *, significant at the 0.05 level; VOSI pre, pretest student VOSI; VOSI post, posttest student VOSI; other abbreviations as in Fig. 1.

Only one teacher characteristic, pretest self-efficacy, moderated one student posttest outcome, content knowledge. Self-efficacy, a well-researched construct (see the supplementary materials for more details), is defined as a teacher's "judgement of his or her capabilities to bring about desired outcomes of student engagement and learning" (*27*). The SSCS effect was positive and large for low values of teacher pretest self-efficacy but decreased as teacher pretest self-efficacy increased (table S2). That is, students in classrooms of teachers who had low teaching self-efficacy at the outset of the study showed a statistically significant increase in their posttest content-knowledge scores, whereas students in classrooms with teachers who had high initial self-efficacy did not. Much research has examined how teachers' knowledge, attitudes, and beliefs about their abilities shape and are shaped by their classroom experiences [e.g., (*28*)]; our results suggest that teachers' underlying beliefs, such as self-efficacy, might influence the overall effectiveness of a student-centered curriculum. No teacher moderators were apparent in the delayed posttest results.

A search for possible indirect mechanisms by which the treatment produced its effects on posttest student outcomes resulted in two mediation models. In the first (Fig. 1), both teacher self-efficacy and student models-and-evidence variables mediate the SSCS effect on the student posttest content-knowledge outcome. Indices indicated a good fit of this model to the data. The indirect effect mediated by the teacher posttest self-efficacy measure varied with the level of its pretest measure, being positive and large for low values of teacher pretest self-efficacy but decreasing with increasing levels of the teacher pretest self-efficacy. The indirect effect mediated by student posttest models and evidence was positive, constant, and relatively strong. In this model, the estimated direct effect of the SSCS treatment on student achievement was not statistically significant, so the total effect consisted entirely of the indirect effects of teacher self-efficacy and student understanding of models and evidence. The results of this analysis therefore suggest that the two mediators influence the student content-knowledge outcome somewhat equally in classrooms taught by teachers with lower self-efficacy at the beginning of the project, but the posttest models-and-evidence outcome was the only significant mediator in classrooms taught by teachers who began the project with relatively high levels of self-efficacy (Fig. 2). (See the supplementary materials for more details.)

These results suggest that an emphasis on models and evidence supports students' learning about space-science content. The models-and-evidence instrument was not designed to assess knowledge about models separately from knowledge about evidence, so their individual influences cannot be separated. SSCS students explicitly learned about the nature of both models and evidence in science, as did control-group students, but SSCS students further engaged in activities in which they used and evaluated models. They also were required to provide explicit evidence that supported new science concepts throughout the curriculum, including activities in which they used evidence to support their arguments about scientific explanations. Experience with models and evidence is therefore supported as underpinning content-knowledge learning.

In the second mediation model, the models-and-evidence outcome mediates the SSCS effect on views of scientific inquiry (Fig. 3). This indirect effect was somewhat smaller than the direct effect of SSCS, but the odds ratio of 1.21 for the indirect path was nevertheless large enough to be of practical importance. The results of this analysis suggest that the emphasis on models and evidence supports students' learning about the endeavor of science.

These findings should also be considered in light of the contradictory results of the previous large-scale studies on the effects of student-centered instruction. In contrast to the common research practice of comparing the treatment group to a control group in which the instructional approach is not specified (i.e., to whatever else is present in schools), our research design tightly controlled the curriculum and instructional approach employed by the treatment and control groups. Further, fidelity was monitored through classroom observations and assessed with RTOP. We argue that this attention to the control group and our efforts to monitor fidelity within both groups sets our study apart from others, and the failure to identify central components of the control group may account for the contradictory nature of previous results.

The increased outcomes of the treatment group in comparison with the control group in content knowledge, models and evidence, and VOSI and the size and persistence of the latter two indicate that student-centered instruction supports the development of students who are more proficient in the four strands of scientific proficiency. More specifically, the mediation models suggest that student-centered instruction that engages students in scientific practices such as using models and evidence is important for developing more scientifically proficient students. Taken together, the results of our study lend empirical support to the view put forth by the National Research Council that "teaching content alone is not likely to lead to proficiency in science, nor is engaging in inquiry experiences devoid of meaningful science content. In current practice, content and an oversimplified view of scientific processes are often the primary or even sole foci of instruction…[and] leads to a very impoverished understanding of science and masks the complex process involved in developing scientific evidence and explanations" [(*3*), p. 335)].

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Supplementary Materials
www.sciencemag.org/cgi/content/full/338/6103/105/DC1
Materials and Methods
Fig. S1
Tables S1 and S2
References (*29–37*)
Student Data Archive

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Wnt5a Potentiates TGF-β Signaling to Promote Colonic Crypt Regeneration After Tissue Injury

Hiroyuki Miyoshi,[1] Rieko Ajima,[2]* Christine T. Luo,[1] Terry P. Yamaguchi,[2]† Thaddeus S. Stappenbeck[1]†

Reestablishing homeostasis after tissue damage depends on the proper organization of stem cells and their progeny, though the repair mechanisms are unclear. The mammalian intestinal epithelium is well suited to approach this problem, as it is composed of well-delineated units called crypts of Lieberkühn. We found that Wnt5a, a noncanonical Wnt ligand, was required for crypt regeneration after injury in mice. Unlike controls, Wnt5a-deficient mice maintained an expanded population of proliferative epithelial cells in the wound. We used an in vitro system to enrich for intestinal epithelial stem cells to discover that Wnt5a inhibited proliferation of these cells. Surprisingly, the effects of Wnt5a were mediated by activation of transforming growth factor–β (TGF-β) signaling. These findings suggest a Wnt5a-dependent mechanism for forming new crypt units to reestablish homeostasis.

Tissue regeneration requires proper spatial allocation and organization of stem cells for efficient return to homeostasis (*1*, *2*). Crypts of Lieberkühn are subunits that house intestinal stem cells and are lost in response to a variety of insults, including ischemia, infection, irradiation, and inflammatory bowel disease (*3*). Although individual crypts undergo fission to replicate during homeostasis (fig. S1A) (*4*, *5*), the mechanism of their regeneration is unknown. Thus, crypt regeneration is a proxy for proper stem cell organization and provides an excellent system to uncover the principles underlying stem cell replacement and/or organization in vivo.

To model crypt/epithelial stem cell loss, we previously developed an injury system to focally