Impact of an Inquiry-Oriented Intervention on Teaching and Learning of Seventh-Grade Statistics

Background and Purpose

Data analysis and statistical thinking have become an integral part of nearly all branches of the natural sciences, social sciences, government, politics, and business. The Bureau of Labor Statistics (2021) predicted that jobs related to statistics are expected to grow 34 percent during the 2020s—much faster than the average expected growth rate for all occupations. Statistical thinking and data literacy—which includes critical thinking and an understanding of how data can be used to inform or to mislead—is also needed outside the workforce. Statistical literacy among voters is an essential competency for citizens in a healthy democracy (Franklin et al., 2015; Wild & Pfannkuch, 1999). Gould declared, "citizenship is often cited as a reason for advancing statistical literacy, since democracies require informed debate, and almost all policy discussions require some statistical understanding" (2017, p. 22).

Responding to the need for a statistically literate population, U.S. educational systems have begun to integrate more probability and statistics content into their K–12 curriculum (Schaeffer & Jacobbe, 2014; Weiland & Sundrani, 2022). This integration started in earnest in the 1990s and increased sharply in 2010 after the release of the Common Core State Standards for Mathematics (CCSSM; NGA & CCSSO, 2010). In Florida, for example, the proportion of content standards from the statistics and probability domain in the course description for seventh-grade mathematics (age 13) increased from 18% prior to adoption of the CCSSM to 33% after adoption. The proportion of content standards in the Algebra 1 course description in Florida increased from 0% statistics in the 2000s to 16% statistics in the 2010s (Authors, 2019).

Statistics could be taught in a variety of subject areas in school (e.g., earth science, social studies, computer science, mathematics) or as a stand-alone discipline (Usiskin & Hall, 2015). Statistics is often considered a branch of the mathematical sciences, but many aspects of statistics are not mathematical (Little, 2013). While it is impossible to understand statistical concepts without a firm understanding of mathematics, this is also true of many other fields, such as physics, astronomy, and engineering. At the secondary level, the responsibility for teaching statistics is primarily assigned to mathematics teachers.

The subject-matter knowledge and pedagogical skills required to teach statistics are different from those required to teach mathematics. Statistics is frequently identified as the topic for which mathematics teachers have the greatest need for professional learning in terms of both content and pedagogy (CBMS, 2001; 2012; Franklin et al., 2015; Groth, 2007). Despite this recognized need, teacher preparation programs in the US typically do not require any statistics courses for graduation. Fewer than 1% of colleges and universities offering bachelor's degrees or higher in statistics in the US offer an undergraduate course designed to prepare K–12 (ages 5–18) teachers for teaching statistics (CBMS, 2012).

Secondary-level mathematics teachers understandably tend to emphasize the mathematical aspects of statistics (e.g., calculating measures of central tendency) and marginalize the more scientific aspects. Consequently, opportunities for secondary-level students to learn statistics that are presented in the enacted curriculum tend to emphasize the mathematical aspect of statistics and fail to address other aspects, such as formulating questions, using statistical software, dealing with messy data sets, acknowledging the uncertainty associated with statistical investigations, and interpreting results of statistical inquiry in the context of a statistical investigation (Weiland & Sundrani, 2022). These process-oriented aspects of the statistical problem-solving process also serve as the foundation of the field of data science, which is an emerging discipline in K–12 schools (Gould, 2017).

State curriculum standards for statistics and probability have been strongly influenced by the Guidelines for Assessment and Instruction in Statistics Education I and II (GAISE) reports (Bargagliotti et al., 2020; Franklin et al., 2007). The GAISE reports recommend a four-part instructional design model for lessons in statistics. The four-phase model includes: formulate a statistical question, collect data, analyze data, and interpret the results. The model was informed by observational studies and expert opinion, but it was not subjected to experimental trials, and its efficacy remains an empirical question.

The purpose of the current study was to examine the efficacy of a statistics intervention in seventh-grade statistics teaching and learning. Three research questions guided the analyses.

RQ1. What is the effect of the STEPSS program on statistics instruction, as measured by the IQA?

RQ2. What is the effect of the STEPSS program on student understanding of statistics, as measured by the LOCUS test?

RQ3. To what extent do socioeconomic status of schools; type of class (regular or advanced); student gender, race, or ethnicity; and prior mathematics achievement scores moderate the effect of the STEPSS program on student learning?

Method

The study used a cluster-randomized controlled trial research design with school-level assignment. School-level assignment enabled teachers within the same school to use the same curriculum materials for the statistics unit. The study was preregistered in the Registry for Educational Effectiveness Studies (1637.1v2).

Setting and Sample. The study was conducted in a large, urban school district during the 2018-2019 school year. To be eligible, schools in this district had to have at least 30 seventh-grade mathematics students (regular or advanced) and two or more seventh-grade mathematics teachers. There were 40 schools that met these criteria in May 2018.

Random assignment of eligible schools to one of two treatment conditions occurred in early summer 2018. Twenty of the eligible schools were assigned to the STEPSS condition. The other 20 schools were assigned to the comparison condition, which engaged in practice-as-usual professional development and curriculum use in mathematics and statistics. At the time of random assignment, the percentage of students in these 40 schools who were eligible for free or reduced-price lunch based on their family's annual income ranged from 18 percent to 96 percent with a mean of 71 percent. In the same school year, the percentage of students scoring proficient on the seventh-grade state mathematics state assessment in those 40 schools ranged from 6 to 87 percent with a mean of 47 percent.

A total of 74 teachers in 26 schools participated in the study of instructional outcomes. A total of 3,607 students in 31 schools for whom affirmative parental consent and student assent was obtained were enrolled in the study. Figures B1 and B2 contain flow diagrams for the studies of impact on statistics instruction and student learning, respectively.

Description of the Intervention. The intervention consisted of a combined curriculum replacement unit and associated professional development program for seventh-grade mathematics teachers and their students. The curriculum unit consists of a set of 12 lessons drawn from publicly available sources (Franklin et al., 2020; Hopfensperger et al., 2012; Jacobbe et al., 2023a; Kader et al., 2020). Each lesson used the four-phase instructional design model described in the GAISE reports. The set of lessons in the curriculum unit was designed to align with the Florida statistics and probability curriculum standards and require approximately 20 days of instruction to implement. Lesson plans, consumable student booklets, and ancillary materials were provided to schools for use by teachers and students in the STEPSS condition.

Teachers in the *STEPSS* program participated in four days of professional-development workshops designed specifically to support implementation of the curriculum resources. During the first three days, teachers experienced each of the 12 lessons in the role of a student and then reflected on the lessons after each lesson. This design attempted to maximizing the coherence between the professional development and curriculum components of the intervention. On the fourth day, teachers prepared to teach those lessons by practicing microteaching lesson study (Fernández, 2005; 2010; Zhou & Xu, 2017). The extent to which teachers in comparison schools participated in alternative professional development opportunities in probability or statistics during the intervention period is also unknown, but curriculum leaders from the school districts report few or no professional development opportunities for teachers in this content area.

Counterfactual Condition. Teachers of seventh-grade mathematics classes in control schools continued with practice-as-usual statistics instruction and professional learning during the study period. The district-adopted textbook was Houghton Mifflin Harcourt's *GO Math!* (Burger et al., 2016). The recommended pacing guide from the district's curriculum department allocated 24 days for the unit on probability and statistics in the regular seventh-grade mathematics course and 19 days in the advanced course. The district also had a local-control policy (i.e., teachers were expected to adjust the pacing according to the needs of their students).

Data Sources.

Student and School Demographics. The school district provided demographic information and sixth-grade mathematics scores on the Florida Standards Assessment (FSA; FLDOE, 2018) for students whose parents consented to sharing data.

Implementation. To measure implementation of key components of the STEPSS intervention in the classroom, classroom observers recorded the following information: standard(s) being taught, source of the enacted lesson(s), phase(s) of statistical investigation enacted during the lesson, and whether students were involved in data production. These factors provide a measure of implementation of features that are central to the design of the lessons in the curriculum replacement unit.

Statistics Instruction. Classroom observers rated the statistics instruction using the Instructional Quality Assessment (IQA; Boston, 2012). The IQA measures several components of classroom instruction, organized into two broad categories: cognitive demand of student tasks, and accountable talk (Resnick et al., 2018; Stein et al., 1997). The IQA instrument contains nine individual rubrics. Each rubric uses a 5-point Likert-type scale, with a minimum of 0 and a maximum of 4. The IQA data were scored using a many-facet Rasch (MFR) model (Linacre, 1989; Authors, 2021; Wind & Jones, 2019). In a MFR model, any variable that has a systematic effect on the observed ratings can be a facet. We fit a three-facet Rasch model to the data. The three facets were: item, rater, and class. The separation index for the items was 12.47. The item reliability was .99. Separation reliability of raters was .68. The range of class (theta) estimates was large, with a maximum of 6.11 and minimum of -4.99. Class reliability was .93, and class separation index was 3.54, indicating a large amount of variation in instructional experiences among classes, and the IQA-score reliability was sufficiently high.

Student Understanding of Statistics. Classroom teachers administered the 23-item, paper-pencil, Beginner/Intermediate, Form 1 of the Levels of Conceptual Understanding in Statistics (LOCUS) test to participating students (Jacobbe et al., 2023b). LOCUS scale scores are generated by models based on item response theory. Twenty of the original 23 items on the test form contributed to the final student scores; the remaining 3 items were excluded due to poor discrimination estimates using the current study data (Huggins-Manley & Jacobbe, 2019). The current study placed the student ability estimates on a scale from 20 to 80, with a mean of 50 and a standard deviation of 10. The marginal reliability of LOCUS scale with this sample was 0.68.

Data Analysis. Hierarchical Linear Models (HLMs) were employed to estimate: (RQ1) the impact of the STEPSS program on instructional practice, (RQ2) the overall impact of the STEPSS program on student understanding of statistics and (RQ3) the impact of the STEPSS program within important student subgroups. The impact of the STEPSS program on instructional practice was estimated using two-level HLMs with teachers nested within schools. The impact of the STEPSS program on student understanding in statistics was estimated using three-level HLMs with students nested within teachers and teachers nested within schools. Statistical models to estimate subgroup effects were specified in a manner similar to those for RQs 1 and 2, except the intercept term was suppressed, indicator variables for each subgroup of interest were inserted into the model, and interactions between the subgroup indicators and the *STEPSS* indicator were also included.

Findings

Implementation of the STEPSS Unit. Statistics instruction in STEPSS schools consistently involved the program's lessons provided in the statistics replacement unit. Teachers used lessons from the STEPPS program curriculum in 95 percent of the classrooms observed in STEPSS program schools. Lessons from the STEPSS program curriculum were never used in the classrooms observed in the practice-as-usual schools. This measure of fidelity of implementation indicates a sharp treatment contrast with respect to the instructional materials used to teach statistics by the schools assigned to the STEPSS program and those in the comparison condition.

Each lesson plan in the STEPSS program curriculum is designed to involve all four phases of statistical investigation, as described in *Guidelines for Assessment and Instruction in Statistics Education* (Franklin et al., 2007). Nearly all the lessons observed in both treatment conditions involved students in the analyze-data phase, which includes practices that mathematics teachers recognize as quantitative and mathematical in nature. Almost all lessons in STEPSS-condition schools involved students in the collect-data phase, compared with 40 percent of lessons in practice-as-usual schools. The percentage of lessons that involved students in the formulate-a-statistical-question phase was higher in STEPSS program schools than in practice-as-usual schools. Lessons in both STEPSS program schools and practice-as-usual schools infrequently involved students in the interpret-results phase.

RQ1. Statistics instruction in STEPSS program schools scored higher on the IQA than statistics instruction in practice-as-usual schools (Table B3). The mean difference in scores is equivalent to an effect size of 0.99 (p=.001).

RQ2. Students in STEPSS program schools scored higher on the Levels of Conceptual Understanding in Statistics test than students in practice-as-usual schools (Table B3). The mean difference is equivalent to an effect size of 0.25 (p=.030).

RQ3. Students in all race/ethnicity groups appeared to benefit from the STEPSS intervention (Table B3). Effects were largest for White students. Both male and female students benefited from STEPSS, with larger effects estimated for males. Students in both advanced and standard classrooms experienced positive effects from STEPSS, with slightly larger effects estimated for those in standard classrooms. Moderation analyses suggest that STEPSS appears to work equally well for students from different socioeconomic backgrounds and different levels of pre-intervention mathematics achievement.

Discussion

Teachers in the control condition primarily emphasized the mathematical aspects of statistical investigations (i.e., analyze data) and did not emphasize the more scientific aspects (i.e., formulate a question that anticipates variation and can be answered by data, plan to collect and gather data, interpret results in context of the original question). The STEPSS program had a positive impact on IQA scores, suggesting that the inquiry-oriented instructional design model used in the lessons in the STEPSS curriculum increased cognitive demand and accountable talk among students. The STEPSS program also had a large, positive effect—25 percent of one standard deviation—on student understanding of statistics.

Implications. On average, students' overall mathematics achievement on nationally normed tests increases by about 0.23 standard deviation in grade 7 (Hill et al., 2008), suggesting that the STEPSS program may have doubled students' rate of learning of statistics compared with their peers in practice-as-usual schools. Mathematics programs that are subjected to randomized controlled trials rarely result in positive effects on student performance of that magnitude (Kraft, 2020). These findings place the STEPSS program on the short list of programs that have been subjected to a randomized controlled trial and found to have a positive effect on student achievement and classroom instruction.

In Florida, content standards in the probability and statistics domain account for approximately one-third of the standards in the grade 7 mathematics course description, but the STEPSS curriculum unit requires only four weeks to implement—or 10–15 percent of the school year. The STEPSS curriculum unit addresses all the benchmarks in the content standards in the regular and advanced grade 7 mathematics course descriptions and is easily implemented in schools. STEPSS can be used to replace existing curriculum in the short term. In the longer term, curriculum developers may consider incorporating the instructional design principles in the STEPSS program lessons into their own curricula for this domain.

Limitations. The design of this study does not enable the disaggregation of the professional-learning and curriculum components, so we do not know whether the impact on instructional practice would have occurred if only one component were present. A higher percentage of teachers STEPSS-condition schools than teachers in comparison schools allowed the study team to observe their classrooms, so these results should be interpreted with caution.

Next Steps. The program appears to benefit all subgroups of students, but the reasons for the larger effects on White and male students—as compared with minority and female students—should be further explored. Systematic replication of this study is needed so that the field may better understand whether these effects can generalize to other settings, grade levels and topics in statistics. The study occurred in a large, urban school district, and the extent to which these results generalize to other settings is not currently known. A replication study should also use a delayed assessment of student understanding to find out whether the effects on students persist after cessation of the intervention.

Conclusions. This study represents the first experimental trial of an influential instructional design model promoted by the statistics educators and the American Statistical Association. Many statistics educators have reached consensus about the value of these design features for student learning, but this approach to teaching statistics had not previously been the subject of experimental trials. The results of this study lend support to the belief that the inquiry-oriented instructional design model used in the STEPSS curriculum and the associated teacher professional learning opportunities for mathematics teachers can have a positive impact on the teaching and learning of statistics.

Appendix A - References

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Appendix B - Tables and Figures

Table B1

Analytic Sample Descriptives for Outcome Variables and Covariates, Split by Condition

Construct	Category	STEPSS	Control
Student Demographics and Baseline Achievement Scores			
Gender	Female	695 (53%)	544 (56%)
	Male	617 (47%)	427 (44%)
Race/ethnicity	Hispanic	420 (32%)	353 (36%)
	Black	400 (31%)	229 (24%)
	White	397 (30%)	328 (34%)
	Asian	54 (4%)	35 (4%)
	Other	41 (3%)	26 (3%)
Math course	Advanced	722 (55%)	521 (54%)
	Regular	590 (45%)	450 (46%)
SES band	1	40 (3%)	40 (4%)
	2	0 (0%)	26 (3%)
	3	586 (45%)	55 (6%)
	4	98 (8%)	42 (4%)
	5	29 (2%)	122 (13%)
	6	136 (10%)	217 (22%)
	7	0 (0%)	2 (0%)
	8	97 (7%)	467 (48%)
	9	0 (0%)	0 (0%)
	10	326 (25%)	0 (0%)
Mathematics pretest	Sixth-grade FSA scaled score mean (s.d.)	327.24 (21.46)	328.31 (22.21)
Outcomes			
Instructional practice	IQA theta estimate mean (s.d.)	0.44 (1.78)	–1.43 (1.87)
Statistics posttest	LOCUS scaled score mean (s.d.)	50.67 (8.31)	49.56 (8.07)

Notes. Gender and race/ethnicity categories were provided by the school district and reflect the categories as reported to the state of Florida; Other is a combination of multiracial and Native American categories. SES Band is an ordinal variable constructed by the school district based on the percentage of students in the school who were eligible for free or reduced-price lunch based on their family's annual income. Test averages are unweighted means of student scores. Parentheses represent percentages within each category within a given condition (STEPSS or Control) unless otherwise indicated. STEPSS analytic sample contains 17 schools, 47 teachers, and 1,312 students. Control analytic sample contains 14 schools, 39 teachers, and 971 students.

Table B2

Implementation of Key Features of the STEPPS Intervention During Observed Lessons, Split by Treatment Condition

	STEPSS condition (*n*=39) Number (proportion within condition)	Control condition (*n*=35) Number (proportion within condition)
	Source of enacted lesson	
District-adopted textbook	2 (.05)	14 (.40)
STEPSS replacement unit	37 (.95)	0 (.00)
Other	0 (.00)	21 (.60)
	Phase(s) of statistical investigation	
Formulate a statistical question	13 (.33)	2 (.06)
Generate data	38 (.97)	14 (.40)
Analyze data	38 (.97)	34 (.97)
Interpret results	5 (.13)	6 (.17)
	Source of data	
Produced by students	38 (.97)	14 (.40)
Provided by teacher	0 (.00)	20 (.57)
No data use	1 (.03)	1 (.03)

Note. Observations occurred in 39 classrooms in 14 STEPSS-condition schools and in 35 classrooms in 12 practice-as-usual schools.

Table B3

Results of Impact, Subgroup, and Moderation Analyses

	Estimate (SE)	*p*-value	Effect size
Overall			
IQA (statistics instruction)	1.81 (0.46)	0.001	0.99
LOCUS (student understanding of statistics)	2.10 (0.87)	0.03	0.25
Impact on LOCUS within subgroups			
Race/Ethnicity subgroups			
Hispanic (*n*=773)	1.82 (0.97)	0.073	0.22
White (*n*=725)	3.39 (1.01)	0.002	0.40
Black (*n*=629)	1.63 (0.99)	0.111	0.19
Other (*n*=67)	1.21 (1.34)	0.367	0.14
Gender subgroups			
Female (*n*=1,239)	1.80 (0.90)	0.060	0.21
Male (*n*=1,044)	2.47 (0.92)	0.014	0.30
Advanced class subgroups			
Advanced class (*n*=1,243)	1.89 (0.95)	0.058	0.23
Standard class (*n*=1,040)	2.26 (0.92)	0.002	0.27
Moderation of impact on LOCUS			
SES Band moderator			
Main effect	2.19 (0.98)	0.05	0.26
SES Band centered	0.06 (0.38)	0.89	0.01
FSA moderator			
Main effect	2.03 (0.87)	0.03	0.24
FSA student score centered	-0.00 (0.02)	0.88	-0.00

Note. Moderator variables were centered to ease interpretation of the main effect.

Figure B1

Flow Diagram for the Study of Instructional Outcomes

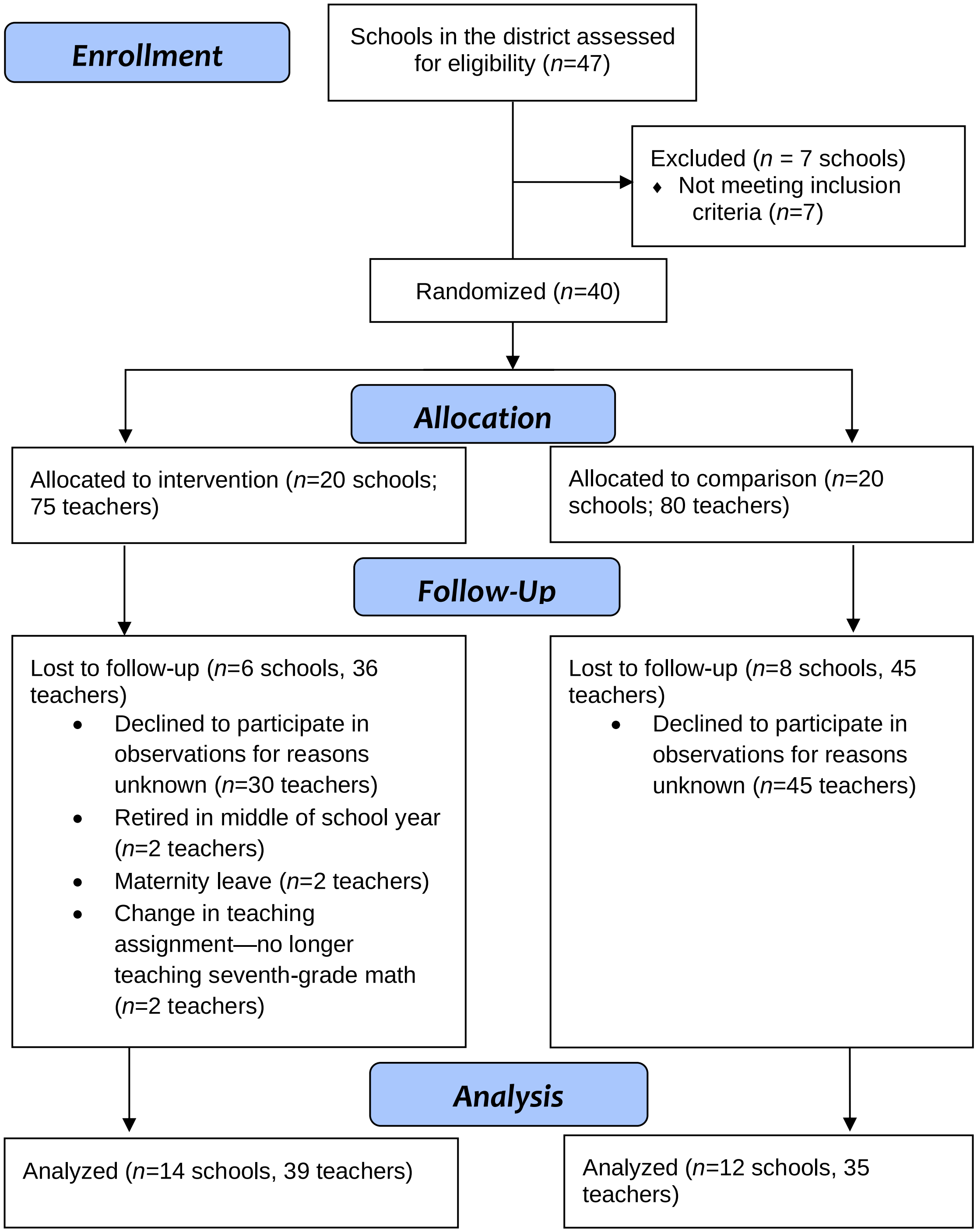

Figure B2

Flow Diagram for the Study of Student Understanding of Statistics