Abstract Title Page

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Title: Effects of Manipulative Use on PK-12 Mathematics Achievement: A Meta-Analysis

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Abstract Body

Background / Context:

There is growing consensus among researchers, educators, and policy makers about the need for greater emphasis on ambitious student-centered mathematics instruction in light of mounting concern about student mathematics performance in the intermediate grades and beyond. To facilitate educators' adoption of ambitious mathematics instructional practices, recent reform initiatives, such as the Common Core Standards for Mathematics (CCSM), have specified the content elementary students should learn and the practices in which students should engage, while organizations such as the National Council of Teachers of Mathematics (NCTM) have assumed responsibility for making recommendations for improving instructional practices in mathematics. In particular, since 1989, the NCTM has continually called for the increased use of manipulative materials at all levels of mathematics education in order to support students' conceptual and procedural understanding. However, the evidence for the effects of using manipulatives to support student mathematics achievement across the primary and secondary grades is generally mixed. Investigating reasons for such contradictory findings through rigorous inquiry is important for advancing both theory and practice in mathematics education. The present systematic review and meta-analysis seeks to address this issue in order to strengthen communication and research partnerships with educators, administrators, and policy makers interested in effective practices in mathematics education.

Constructivist theories of learning postulate that students build increasingly complex knowledge through active engagement with concrete materials such as manipulatives (Bruner, 1977; Dienes, 1973; Piaget, 1965). Manipulative materials have been defined in the literature as "objects that appeal to several senses and that can be touched, moved about, rearranged, and otherwise handled by children" (Kennedy, 1986, p. 6), while other scholars have added that manipulatives should introduce or reinforce mathematical concepts (Hartshorn & Boren, 1990) and strengthen students' representation of mathematical ideas (Clements, 1999). Thus, manipulatives are concrete objects or virtual representations of objects that students can move in order to study their mathematical properties, which supports students' progression from concrete to increasingly abstract ways of thinking about a number of diverse mathematical ideas.

Manipulatives can be simple household items such as buttons or dice, though commercially manufactured products designed to meet general or specific educational aims (e.g., Legos, puzzles, pattern blocks, Unifix cubes) are also widely available (Spikell, 1993). More recently, advances in educational technology have led to the creation of virtual manipulatives. Virtual manipulatives are computer applications or applets that enable students to manipulate virtual replicas of physical manipulatives (Reimer & Moyer, 2005). Through interaction with manipulatives, students can thus relate mathematical concepts and ideas to practical, real-world experiences (Rittle-Johnson & Koedinger, 2005).

In recent years, there has been a proliferation of mathematics curricula that involve the use of manipulative materials, and many student-centered classrooms frequently employ the use of manipulatives during mathematics instruction. However, despite the wide availability of manipulatives and repeated calls for their use, some teachers continue to use more traditional approaches to mathematics instruction, citing cost, time constraints, incongruence with skills measured on standardized assessments, and lack of training in how to teach using manipulatives (Tooke, Hyatt, Leigh, Snyder, & Borda, 1992; Worth, 1986). Along these same lines, critics of the hands-on approach to mathematics have noted that the simple provision of manipulative materials is not likely to result in learning without specific instruction that supports students' model-based reasoning and conceptual understanding, which necessitates extensive teacher preparation and professional development in how children learn (Ball, 1992; Gravemeijer, 1997; Grouws & Cebulla, 2000).

Thus, in order to inform the development of instructional materials and teacher training programs emphasizing manipulative use, it is important to establish an evidentiary basis for the use of manipulatives as an effective instructional practice in mathematics and to examine aspects of program implementation that may be associated with greater effectiveness. To this end, the purpose of the present review is to summarize the existing evidence for manipulatives interventions and to investigate differential effects associated with participant, program, and study design characteristics.

An extensive literature search revealed three prior reviews and five meta-analyses focused on comparing manipulative use to traditional instructional methods in mathematics. However, findings and conclusions differed in important ways and suggested variables potentially associated with differential intervention effects. Early reviews (i.e., Fennema, 1972; Suydam & Higgins, 1977) suggested that manipulatives supported student understanding of underlying mathematical concepts but reached different conclusions about differential effects based on student grade level. An annotated bibliography compiled by Gerling and Wood (1976) listed 103 research studies conducted from 1970 to 1975 on the use of manipulatives, but no conclusions were drawn about the effectiveness of manipulative use on learning.

Later meta-analyses also yielded conflicting findings. For example, Parham (1983) obtained a mean effect size of 1.03 for the effect of manipulative use on student achievement compared to nonuse in grades 1-6, whereas Sutawidjaja's (1987) meta-analysis focused on primary grades students found an overall mean effect size of zero, thus finding no evidence for an effect of using manipulatives. More recently, Domino (2010) conducted a meta-analysis of physical manipulatives use in grades K-6 from 1989 to 2010, finding an overall effect size of 0.50. Regarding differential effects due to participant and intervention characteristics, Parham (1983) found that being in an intermediate grade level was associated with larger effects, whereas LeNoir (1989) found stronger effects for manipulative use by students above fifth grade. Sowell (1989) meta-analyzed 60 studies from 1954 to 1987 of students in kindergarten through college, finding that only when students in the elementary grades used manipulatives for a school year or more did their achievement improve. However, Sowell did not report a mean effect size for her group of studies. Domino's (2010) work also suggested that participant, program, and study characteristics may be associated with differential effects, but the author estimated some of this information, thus potentially biasing the results of any moderator analyses conducted.

Purpose / Objective / Research Question / Focus of Study:

Taken together, the evidence for the effects of using manipulatives to support student mathematics achievement across the primary and secondary grades is generally mixed and merits further scrutiny. Although some reviews reported positive effects for manipulative use, effects differed based on population and program characteristics. In addition, no published meta-analytic reviews about the effects of virtual manipulatives exist, despite their increasing availability and use in mathematics classrooms. Since much of the literature about manipulative use is unpublished, especially recent studies involving virtual manipulative use, a meta-analysis investigating both physical and virtual manipulatives may help communicate these findings to scholars, practitioners, and policy makers alike.

Consequently, the present meta-analysis sought to address these gaps in the literature by conducting a systematic review of interventions involving children's manipulative use in prekindergarten through grade 12 to increase student mathematics achievement. The main purpose of this systematic review was to summarize the available evidence on the effects of using manipulatives during mathematics instruction to increase student mathematics achievement in preschool through twelfth grade. A key focus of the analysis was to examine the comparative effectiveness of virtual and physical manipulatives and to explore differential effects associated with program and participant characteristics. Specifically, the *a priori* effect size moderators of interest were as follows: manipulatives type, program duration, gender mix of participants, and grade level of participants. The research questions investigated in this review are as follows:

1. How effective is the use of manipulatives during mathematics instruction in improving students' mathematics achievement in preschool through twelfth grade compared to instruction that does not involve manipulative use?
2. Is the use of virtual manipulatives during mathematics instruction more effective in improving students' mathematics achievement in preschool through twelfth grade compared to the use of physical manipulatives in mathematics instruction?
3. Is the use of manipulatives during mathematics instruction more effective in improving mathematics achievement for students in grades PK-8 than for students in grades 9-12?
4. Is the use of manipulatives during mathematics instruction more effective in improving mathematics achievement in grades PK-12 for groups with higher percentages of male students?
5. Is duration of mathematics instruction with manipulatives associated with differential effects on student mathematics achievement in grades PK-12?

Data Collection and Analysis:

A comprehensive literature search was conducted to identify qualifying studies reported between 1989 and 2012, including a search of electronic bibliographic databases, gray literature databases, and reference lists of research reports and prior reviews. To qualify for inclusion, primary studies had to investigate an intervention focused on children's use of physical or virtual manipulative materials during school-based mathematics instruction among school-aged populations of children who would be expected to attend prekindergarten through twelfth grade or the equivalent. Studies had to use an eligible randomized or quasi-experimental design with a non-use or business as usual control group and report quantitative mathematics achievement outcome data permitting the calculation of an effect size. Finally, studies had to be reported in English in 1989 or later to be relevant to a contemporary student population and due to the researcher's available resources.

The search culminated in a total of 856 reports, of which 17 reports describing 21 primary studies met the eligibility criteria after screening of titles, abstracts, and/or full-text reports, for a total sample of 1519 students. Random-effects inverse variance weighted meta-analytic methods were used to synthesize standardized mean difference effect sizes for the math achievement outcomes. Meta-regression models were used to examine the effects of different study, participant, and program characteristics on the effect sizes. Funnel plots, regression-based tests for small sample bias, and trim and fill analyses were used to assess the potential for publication bias. Sensitivity analyses were used to assess decisions associated with the inclusion of quasi-experimental designs and the Winsorizing of an outlying effect size from a randomized study of questionable implementation quality.

Findings / Results:

Two separate meta-analyses were conducted for the comparison of manipulatives use to a business as usual nonuse condition (14 studies, 14 effect sizes, 1126 students) and for the comparison of virtual manipulatives use to a business as usual physical manipulatives use condition (7 studies, 7 effect sizes, 393 students). Characteristics of statistics are presented in Table 1 (insert Table 1 here), and descriptive statistics are presented in Table 2 (insert Table 2 here). As shown in Figure 1 (insert Figure 1 here), the random effects weighted standardized mean difference effect size for the effect of manipulatives use to nonuse was 0.22, which translates to a mathematics achievement percentile gain of 9%. These results indicated that students who used manipulatives during mathematics instruction had statistically significant higher mathematics achievement than students who did not use manipulatives during mathematics instruction and performed approximately one-fifth of a standard deviation higher on mathematics outcome measures than their peers in the control condition. As shown in Figure 2 (insert Figure 2 here), the statistically non-significant random effects weighted standardized mean difference effect size for the effect of virtual manipulatives use compared to physical manipulatives use was 0.20, which translates to a mathematics achievement percentile gain of 8%. These results indicated that students who used virtual manipulatives during mathematics instruction performed one-fifth of a standard deviation higher on mathematics outcome measures of achievement than their peers who used physical manipulatives during mathematics instruction. Although moderator analyses were inconclusive (insert Table 3 here), there was some evidence suggesting that virtual manipulatives use was associated with larger effects than physical manipulatives use and that randomized designs reported smaller effect sizes. Limited evidence for publication bias due to small study effects was found in both meta-analyses, as shown in Figure 3 (insert Figure 3 here) and Figure 4 (insert Figure 4 here). Sensitivity analyses affirmed the analytic decision to Winsorize the questionable study outlier.

Conclusions:

Although clearly not a mathematics achievement panacea, results from this review provide evidence that student achievement in grades PK-12 can be improved through the use of mathematics manipulatives. An estimated mean effect size of 0.22 and 0.20 is comparable to the demonstrated effectiveness of other educational interventions found by Bloom and colleagues (2008). Bloom et al. (2008) noted that effect sizes for annual achievement gains made by high school students were 0.20 and lower, compared to those for the yearly gains of primary grades students at nearly 1.0. Thus, the practical significance of the estimated mean effect sizes in this review may appear more consequential when compared to the added value of attending school one more year at the secondary level but seem less consequential alongside the growth exhibited by children in the first years of formal schooling.

Importantly, lack of discernable heterogeneity in effect sizes may also suggest these effects are not likely to differ statistically or substantively based on different participant and intervention characteristics. However, more research to investigate a potential trend favoring the use of virtual manipulatives over physical manipulatives is warranted to inform educational decision-making, as this study suffered from a number of limitations due to insufficient reporting from primary research and low power to detect statistically significant predictors of effect size. Among other implications, practitioners, administrators, and policy makers may want to consider purchasing more inexpensive manipulative materials in order to reserve funds for other interventions that research has shown to have a more substantial impact on student mathematics achievement.

Appendices

Appendix A. References

References marked with an asterisk indicate studies included in the meta-analysis.

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Appendix B. Tables and Figures

Table 1

Characteristics of Studies of Manipulatives Use

Variable	*k*	%	*M*	*SD*	*Min*	*Max*
Participant Characteristics						
Percent Male (only 6 studies)			48.06	7.88	28.57	56.00
Grade Level						
K-8	15	71.43				
9-12	5	23.81				
6-12	1	4.76				
Population						
General Education	20	95.24				
Special Education	1	4.76				
Intervention Characteristics						
Duration (in days)			17.74	21.98	1.00	80.00
Setting						
Regular Classroom	20	95.24				
Pull-out Classroom	1	4.76				
Manipulatives Type						
Physical to Nonuse	9	42.86				
Virtual to Nonuse	5	23.81				
Virtual to Physical	7	33.33				
Implementation Quality						
No Apparent Problems	17	80.95				
Possible Problems	3	14.29				
Definite Problems	1	4.76				

Variable	*k*	%	*M*	*SD*	*Min*	*Max*
Study Characteristics						
Design						
Randomized	13	61.90				
Quasi-Experimental	8	38.10				
Assignment Unit						
Child	13	61.90				
Class	8	38.10				
Favored Group						
Equal	11	52.38				
Control	6	28.57				
Treatment	4	19.05				
Outcome						
Performance Index						
Standardized test	17	80.95				
Researcher-created test	2	9.52				
Curricular test	2	9.52				
Mathematics Area						
Algebra Concepts and Skills	8	38.10				
Geometry Concepts and Skills	5	23.81				
Number Sense and Operations	6	28.57				
General Mathematics	2	9.52				
General Characteristics						
Publication Year			2006	4.79	1994	2012
Publication Type						
Conference Report	1	4.76				
Dissertation or Thesis	9	42.86				
Journal Article	11	52.38				
Location						
USA	19	90.48				
Africa	1	4.76				
Asia	1	4.76				

Table 2

Descriptive Statistics for Studies by Meta-Analytic Subgroup and Condition

Study	Control			Experimental			
	N	*M*	*SD*	*N*	*M*	*SD*	*SMD*
Use to Nonuse							
McClung (1998)[a]	23	70.00	7.42	24	52.00	7.42	-0.30
Grupe (2001)[b]	10	-	-	11	-	-	-0.24
Cavanaugh (2008)	14	19.21	7.45	33	18.08	5.69	-0.18
Konold (2004)	62	12.71	2.03	46	12.46	2.04	-0.02
Dean (2007)	7	80.86	9.94	7	80.71	12.62	-0.01
Kanai (1994)	29	16.52	5.10	23	16.78	8.06	0.04
Steen (2006)	15	29.90	1.20	16	30.00	1.00	0.09
Konold (2004)	24	10.75	4.10	37	10.86	4.10	0.13
Sorkin (2011)	50	14.96	9.33	44	17.83	10.54	0.29
Olkun (2003)	31	8.77	4.28	31	9.97	3.81	0.29
Aburime (2009)	91	9.89	5.77	94	11.70	5.26	0.32
Olkun (2003)	31	8.77	4.28	31	10.48	3.36	0.44
Ozel (2009)	14	0.79	5.00	11	3.82	3.66	0.66
Pacilli (2010)	91	60.47	22.60	226	77.07	19.28	0.81
Virtual to Physical							
Burns (2011)	29	7.34	2.55	25	6.66	1.70	-0.30
Moyer (2012)	12	89.08	14.45	12	85.58	17.28	-0.19
Yuan (2010)	30	30.60	2.66	30	30.47	3.18	-0.04
Suh (2007)	18	80.55	21.32	17	83.33	17.32	0.12
Olkun (2003)	31	9.97	3.81	31	10.48	3.36	0.14
Burns (2011)	49	22.57	6.12	42	24.95	4.06	0.45
Mendiburo (2011)[b]	33	-	-	34	-	-	0.51

Note. SMD = standardized mean difference effect size with Hedges' *g* correction and sample size adjustments for clustering at the classroom level applied. Unadjusted sample sizes reported.
[a]The effect size for this study was Winsorized.
[b]Means and standard deviations were not reported in these reports and are thus denoted with a dash. For these studies, effect sizes were derived from test statistics.

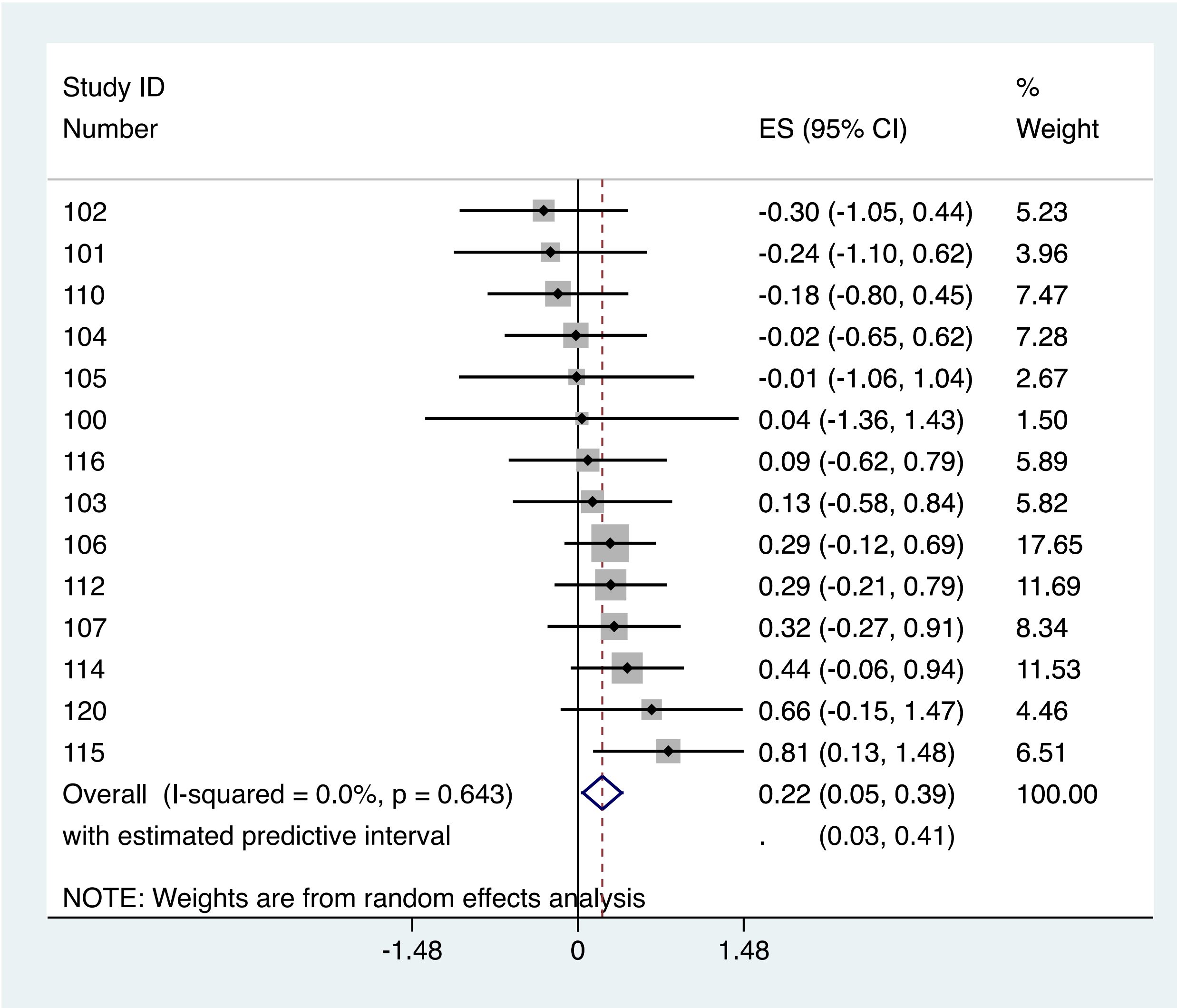

Figure 1. Forest plot for the effect of using manipulatives on student mathematics achievement compared to manipulatives nonuse.

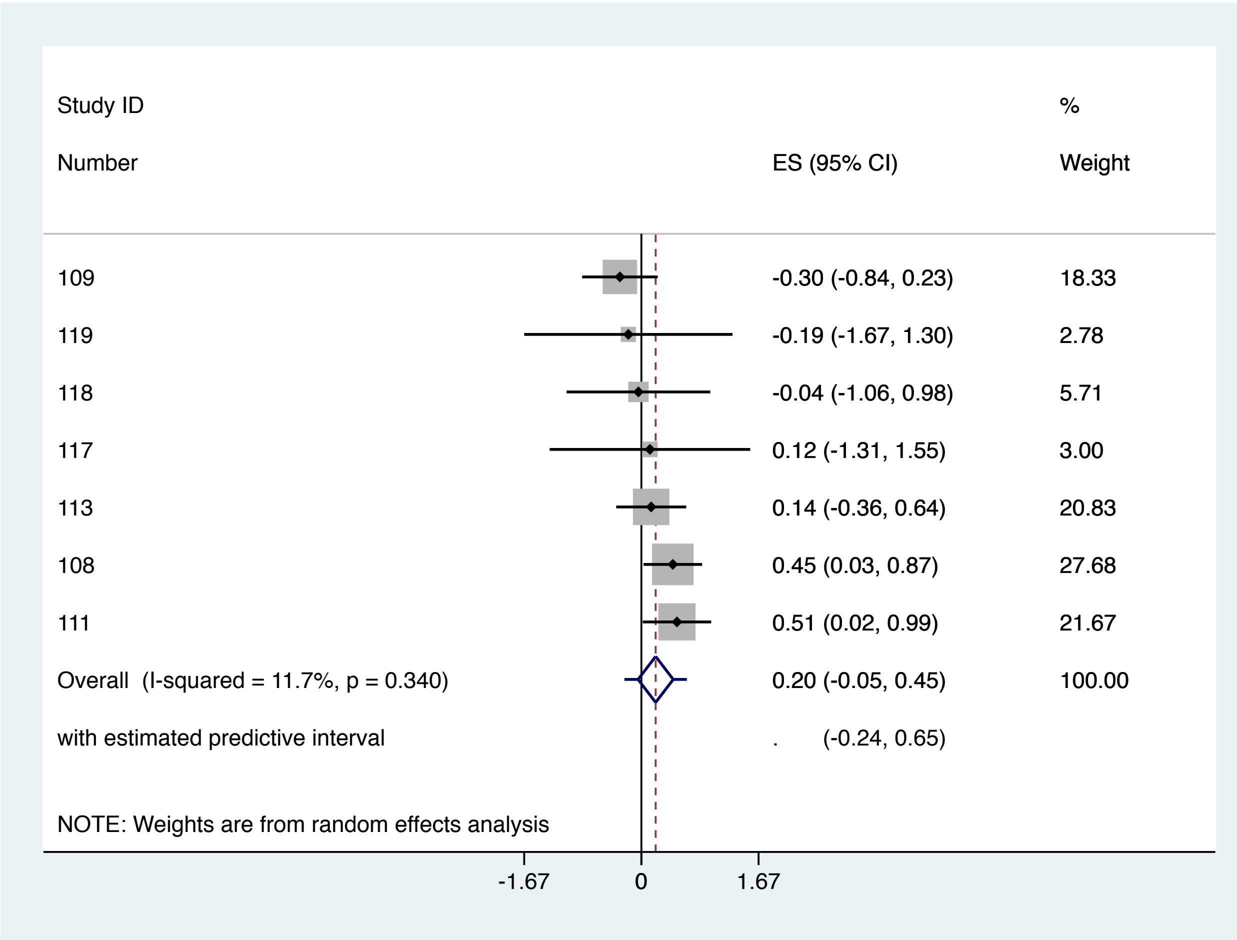

Figure 2. Forest plot for the effect of using virtual manipulatives compared to physical manipulatives on student mathematics achievement.

Table 3

Bivariate Metaregression Models for Participant and Program Characteristics

Variable	Model I	Model II	Model III
Constant	0.31 (.23)	-0.06 (.26)	0.30 (.12)*
Participant Characteristics			
Grade Level	-0.03 (.07)		
Program Characteristics			
Manipulatives Type		0.20 (.18)	
Duration			-0.01 (.00)

* significant at the $p < .05$ level.

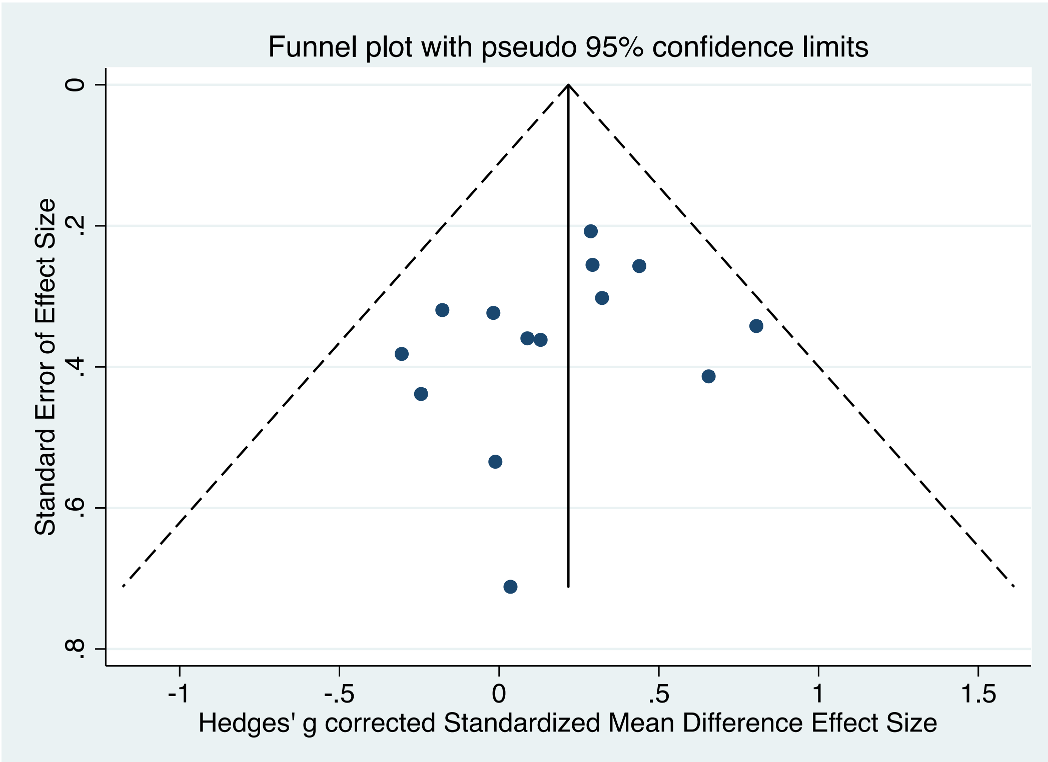

Figure 3. Funnel plot for the effects of manipulatives on math achievement.

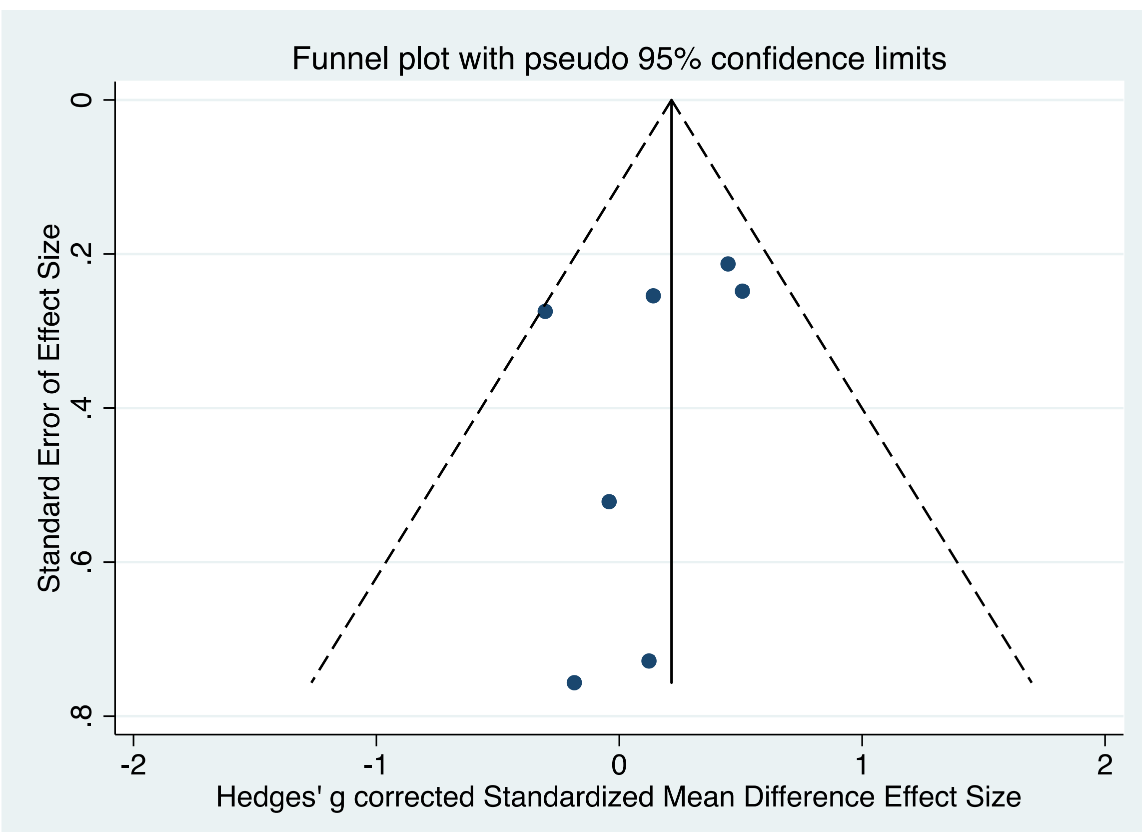

Figure 4. Funnel plot for the effects of virtual manipulatives on math achievement.