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The Malleability of Spatial Skills: A Meta-Analysis of Training Studies

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Having good spatial skills strongly predicts achievement and attainment in science, technology, engineering, and mathematics fields (e.g., Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). Improving spatial skills is therefore of both theoretical and practical importance. To determine whether and to what extent training and experience can improve these skills, we meta-analyzed 217 research studies investigating the magnitude, moderators, durability, and generalizability of training on spatial skills. After eliminating outliers, the average effect size (Hedges's *g*) for training relative to control was 0.47 ($SE = 0.04$). Training effects were stable and were not affected by delays between training and posttesting. Training also transferred to other spatial tasks that were not directly trained. We analyzed the effects of several moderators, including the presence and type of control groups, sex, age, and type of training. Additionally, we included a theoretically motivated typology of spatial skills that emphasizes 2 dimensions: intrinsic versus extrinsic and static versus dynamic (Newcombe & Shipley, in press). Finally, we consider the potential educational and policy implications of directly training spatial skills. Considered together, the results suggest that spatially enriched education could pay substantial dividends in increasing participation in mathematics, science, and engineering.

Keywords: spatial skills, training, meta-analysis, transfer, STEM

The nature and extent of malleability are central questions in developmental and educational psychology (Bornstein, 1989). To what extent can experience alter people's abilities? Does the effect of experience change over time? Are there critical or sensitive periods for influencing development? What are the origins and determinants of individual variation in response to environmental input? Spirited debate on these matters is long-standing, and still continues. However, there is renewed interest in malleability in behavioral and neuroscientific research on development (e.g., M. H. Johnson, Munakata, & Gilmore, 2002; National Research Council [NRC], 2000; Stiles, 2008). Similarly, recent economic, educational, and psychological research has focused on the capacity of educational experiences to maximize human potential, reduce inequality (e.g., Duncan et al., 2007; Heckman & Masterov, 2007), and foster competence in a variety of school subjects, including reading (e.g., Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001), mathematics (e.g., U.S. Department of Education, 2008), and science and engineering (NRC, 2009).

This article develops this theme further, by focusing on the degree of malleability of a specific class of cognitive abilities: spatial skills. These skills are important for a variety of everyday tasks, including tool use and navigation. They also relate to an important national problem: effective education in the science, technology, engineering, and mathematics (STEM) disciplines. Recent analyses have shown that spatial abilities uniquely predict STEM achievement and attainment. For example, in a long-term longitudinal study, using a nationally representative sample, Wai, Lubinski, and Benbow (2009) showed that spatial ability was a significant predictor of achievement in STEM, even after holding constant possible third variables such as mathematics and verbal skills (see also Humphreys, Lubinski, & Yao, 1993; Shea, Lubinski, & Benbow, 2001).

Efforts to improve STEM achievement by improving spatial skills would thus seem logical. However, the success of this strategy is predicated on the assumption that spatial skills are sufficiently malleable to make training effective and economically feasible. Some investigators have argued that training spatial performance leads only to fleeting improvements, limited to cases in which the trained task and outcome measures are very similar (e.g., Eliot, 1987; Eliot & Fralley, 1976; Maccoby & Jacklin, 1974; Sims & Mayer, 2002). In fact, the NRC (2006) report, *Learning to Think Spatially*, questioned the generality of training effects and concluded that transfer of spatial improvements to untrained skills has not been convincingly demonstrated. The report called for research aimed at determining how to improve spatial performance in a generalizable way (NRC, 2006).

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Prior meta-analyses concerned with spatial ability did not focus on the issue of how, and how much, training influences spatial thinking. Nor did they address the vital issues of durability and transfer of training. For example, Linn and Petersen (1985) conducted a comprehensive meta-analysis of sex differences in spatial skills, but they did not examine the effects of training. Closer to the issues at hand, Baenninger and Newcombe (1989) conducted a meta-analysis aimed at determining whether training spatial skills would reduce or eliminate sex differences in spatial reasoning. However, Baenninger and Newcombe's meta-analysis, which is now quite dated, focused almost exclusively on sex differences. It ignored the fundamental questions of durability and transfer of training, although the need to further explore these issues was highlighted in the Discussion section.

Given the new focus on the importance of spatial skills in STEM learning, the time is ripe for a comprehensive, systematic review of the responsiveness of spatial skills to training and experience. The present meta-analytic review examines the existing literature to determine the size of spatial training effects, as well as whether any such training effects are durable and whether they transfer to new tasks. Durability and transfer of training matter substantially. For spatial training to be educationally relevant, its effects must endure longer than a few days, and must show at least some transfer to nontrained problems and tasks. Thus, examining these issues comprehensively may have a considerable impact on educational policy and the continued development of spatial training interventions. Additionally, it may highlight areas that are as of yet underresearched and warrant further study.

Like that of Baenninger and Newcombe (1989), the current study examines sex differences in responsiveness to training. Researchers since Maccoby and Jacklin (1974) have identified spatial skills as an area in which males outperform females on many but not all tasks (Voyer, Voyer, & Bryden, 1995). Some researchers (e.g., Fennema & Sherman, 1977; Sherman, 1967) have suggested that females should improve more with training than males because they have been more deprived of spatial experience. However, Baenninger and Newcombe's meta-analysis showed parallel improvement for the two sexes. This conclusion deserves reevaluation given the many training studies completed since the Baenninger and Newcombe review.

The present study goes beyond the analyses conducted by Baenninger and Newcombe (1989) in evaluating whether those who initially perform poorly on tests of spatial skills can benefit more from training than those who initially perform well. Although the idea that this should be the case that motivated Baenninger and Newcombe to examine whether training had differential effects across the sexes, they did not directly examine the impact of initial performance on the size of training effects observed. Notably, there is considerable variation within the sexes in terms of spatial ability (Astur, Ortiz, & Sutherland, 1998; Linn & Petersen, 1985; Maccoby & Jacklin, 1974; Silverman & Eals, 1992; Voyer et al., 1995). Thus, even if spatial training does not lead to greater effects for females as a group (Baenninger & Newcombe, 1989), it might still lead to greater improvements for those individuals who initially perform particularly poorly. In addition, this review examines whether younger children improve more than adolescents and adults, as a sensitive period hypothesis would predict.

Typology of Spatial Skills

Ideally, a meta-analysis of the responsiveness of spatial skills to training would begin with a precise definition of spatial ability and a clear breakdown of that ability into constituent factors or skills. It would also provide a clear explanation of perceptual and cognitive processes or mechanisms that these different spatial factors demand or tap. The typology would allow for a specification of whether, how, and why the different skills do, or do not, respond to training of various types. Unfortunately, the definition of spatial ability is a matter of contention, and a comprehensive account of the underlying processes is not currently available (Hegarty & Waller, 2005).

Prior attempts at defining and classifying spatial skills have mostly followed a psychometric approach. Research in this tradition typically relies on exploratory factor analysis of the relations among items from different tests that researchers believe sample from the domain of spatial abilities (e.g., Carroll, 1993; Eliot, 1987; Lohman, 1988; Thurstone, 1947). However, like most intelligence tests, tests of spatial ability did not grow out of a clear theoretical account or even a definition of spatial ability. Thus, it is not surprising that the exploratory factor approach has not led to consensus. Instead, it has identified a variety of distinct factors. Agreement seems to be strongest for the existence of a skill often called *spatial visualization*, which involves the ability to imagine and mentally transform spatial information. Support has been less consistent for other factors, such as *spatial orientation*, which involves the ability to imagine oneself or a configuration from different perspectives (Hegarty & Waller, 2005).

Since a century of research on these topics has not led to a clear consensus regarding the definition and subcomponents of spatial ability, a new approach is clearly needed (Hegarty & Waller, 2005; Newcombe & Shipley, in press). Our approach relies on a classification system that grows out of linguistic, cognitive, and neuroscientific investigation (Chatterjee, 2008; Palmer, 1978; Talmy, 2000). The system makes use of two fundamental distinctions. The first is between intrinsic and extrinsic information. Intrinsic information is what one typically thinks about when defining an object. It is the specification of the parts, and the relation between the parts, that defines a particular object (e.g., Biederman, 1987; Hoffman & Singh, 1997; Tversky, 1981). Extrinsic information refers to the relation among objects in a group, relative to one another or to an overall framework. So, for example, the spatial information that allows us to distinguish rakes from hoes from shovels in the garden shed is intrinsic information, whereas the spatial relations among those tools (e.g., the hoe is between the rake and the shovel) are extrinsic, as well as the relations of each object to the wider world (e.g., the rake, hoe, and shovel are all on the north side of the shed, on the side where the brook runs down to the pond). The intrinsic–extrinsic distinction is supported by several lines of research (e.g., Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Huttenlocher & Presson, 1979; Kozhevnikov & Hegarty, 2001; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006).

The second distinction is between static and dynamic tasks. So far, our discussion has focused only on fixed, static information. However, objects can also move or be moved. Such movement can change their intrinsic specification, as when they are folded or cut, or rotated in place. In other cases, movement changes an object's

position with regard to other objects and overall spatial frameworks. The distinction between static and dynamic skills is supported by a variety of research. For example, Kozhevnikov, Hegarty, and Mayer (2002) and Kozhevnikov, Kosslyn, and Shephard (2005) found that object visualizers (who excel at intrinsic–static skills in our terminology) are quite distinct from spatial visualizers (who excel at intrinsic–dynamic skills). Artists are very likely to be object visualizers, whereas scientists are very likely to be spatial visualizers.

Considering the two dimensions together (intrinsic vs. extrinsic, dynamic vs. static) yields a 2 × 2 classification of spatial skills, as shown in Figure 1. The figure also includes well-known examples of the spatial processes that fall within each of the four cells. For example, the recognition of an object as a rake involves intrinsic, static information. In contrast, the mental rotation of the same object involves intrinsic, dynamic information. Thinking about the relations among locations in the environment, or on a map, involves extrinsic, static information. Thinking about how one's perception of the relations among the object would change as one moves through the same environment involves extrinsic, dynamic relation.

Linn and Petersen's (1985) three categories—*spatial perception*, *mental rotation*, and *spatial visualization*—can be mapped onto the cells in our typology. Table 1 provides a mapping of the relation between our classification of spatial skills and Linn and Petersen's.

Linn and Petersen (1985) described spatial perception tasks as those that required participants to "determine spatial relationships with respect to the orientation of their own bodies, in spite of distracting information" (p. 1482). This category represents tasks that are extrinsic and static in our typology because they require the coding of spatial position in relation to another object, or with respect to gravity. Examples of tests in this category are the Rod and Frame Test and the Water-Level Task. Linn and Petersen's mental rotation tasks involved a dynamic process in which a participant attempts to mentally rotate one stimulus to align it with a comparison stimulus and then make a judgment regarding whether the two stimuli appear the same. This category represents tasks that are intrinsic and dynamic in our typology because they involve the transformation of a single object. Examples of mental rotation tests are the Mental Rotations Test (Vandenberg & Kuse, 1978) and the Cards Rotation Test (French, Ekstrom, & Price, 1963).

Linn and Petersen's spatial visualization tasks, as described by Linn and Petersen (1985), were "those spatial ability tasks that involve complicated, multistep manipulations of spatially presented information" (p. 1484). This category included Embedded Figures, Hidden Figures, Paper Folding, Paper Form Board, Surface Development, Differential Aptitude Test (spatial relations subtest), Block Design, and Guilford–Zimmerman spatial visualization tests. The large number of tasks in this category reflects its relative lack of specificity. Although all these tasks require people to think about a single object, and thus are intrinsic in our typology, some tasks, such as the Embedded Figures and Hidden Figures, are static in nature, whereas others, including Paper Folding and Surface Development, require a dynamic mental manipulation of the object. Therefore we feel that the 2 × 2 classification provides a more precise description of the spatial skills and their corresponding tests.

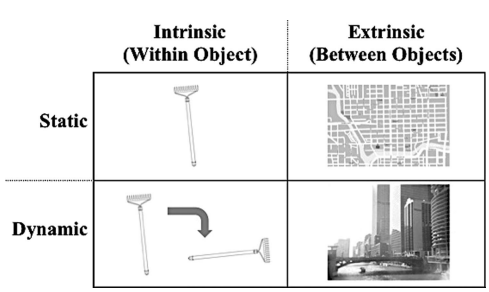

Figure 1. A 2 × 2 classification of spatial skills and examples of each spatial process.

Methodological Considerations

How individual studies are designed, conducted, and analyzed often turns out to be the key to interpreting the results in a meta-analysis (e.g., The Campbell Collaboration, 2001; Lipsey & Wilson, 2001). In this section we describe our approach to dealing with some particularly relevant methodological concerns, including differences in research designs, heterogeneity in effect sizes, and the (potential) analysis of the nonindependence and nested structure of some effect sizes. One of the contributions of the present work is the use of a new method for analyzing and understanding the effects of heterogeneity and nonindependence.

Research Design and Improvement in Control Groups

Research design often turns out to be extremely important in understanding variation in effect sizes. A good example in the present work concerns the influences of variation in control groups and control activities on the interpretation of training-related gains. Although control groups do not, by definition, receive explicit training, they often take the same tests of spatial skills as the experimental groups do. For example, researchers might measure a particular spatial skill in both the treatment and control groups before, during, and after training. Consequently, the performance of both groups could improve due to retesting effects—taking a test multiple times in itself leads to improvement, particularly if the multiply administered tests are identical or similar (Hausknecht, Halpert, Di Paolo, & Gerrard, 2007). Salthouse and Tucker-Drob (2008) have suggested that retesting effects may be particularly large for measures of spatial skills. Consequently, a design that includes no control group might find a very strong effect of training, but this result would be confounded with retesting effects. Likewise, a seemingly very large training effect could be rendered nonsignificant if compared to a control group that greatly improved due to retesting effects (Sims & Mayer, 2002). Thus, it is critically important to consider the presence and performance of control groups.

Three designs have been used in spatial training studies. The first is a simple pretest, posttest design on a single group, which we label the *within-subjects-only* design. The second design involves comparing a training (treatment) group to a control group on a test given after the treatment group receives training. We call this methodology the *between-subjects* design. The final approach is a *mixed* design in which pre- and posttest measures are taken for both the training and

Table 1
Defining Characteristics of the Outcome Measure Categories and Their Correspondence to Categories Used in Prior Research

Spatial skills described by the 2 × 2 classification	Description	Examples of measures	Linn & Petersen (1985)	Carroll (1993)
Intrinsic and static	Perceiving objects, paths, or spatial configurations amid distracting background information	Embedded Figures tasks, flexibility of closure, mazes	Spatial visualization	Visuospatial perceptual speed
Intrinsic and dynamic	Piecing together objects into more complex configurations, visualizing and mentally transforming objects, often from 2-D to 3-D, or vice versa. Rotating 2-D or 3-D objects	Form Board, Block Design, Paper Folding, Mental Cutting, Mental Rotations Test, Cube Comparison, Purdue Spatial Visualization Test, Card Rotation Test	Spatial visualization, mental rotation	Spatial visualization, spatial relations/speeded rotation
Extrinsic and static	Understanding abstract spatial principles, such as horizontal invariance or verticality	Water-Level, Water Clock, Plumb-Line, Cross-Bar, Rod and Frame Test	Spatial perception	Not included
Extrinsic and dynamic	Visualizing an environment in its entirety from a different position	Piaget's Three Mountains Task, Guilford–Zimmerman spatial orientation	Not included	Not included

control groups and the degree of improvement is determined by the difference between the gains made by each group.

The three research designs differ substantially in terms of their contribution to understanding the possible improvement of control groups. Because the within-subjects design does not include a control group, it confounds training and retesting effects. The between-subjects design does include a control group, but performance is measured only once. Thus, only those studies that used the mixed design methodology allow us to calculate the effect sizes for the improvement of the treatment and control groups independently, along with the overall effect size of treatment versus control. Fortunately, this design was the most commonly used among the studies in our meta-analysis, accounting for about 60%. We therefore were able to analyze control and treatment groups separately, allowing us to measure the magnitude of improvement as well as investigate possible explanations for this improvement.

Heterogeneity

We also considered the important methodological issue of heterogeneity. Classic, fixed-effect meta-analyses assume homogeneity—that all studies estimate the same underlying effect size. However, this assumption is, in practice, rarely met. Because we included a variety of types of training and outcome measures, it is important that we account for heterogeneity in our analyses.

Prior meta-analyses have often handled heterogeneity by parsing the data set into smaller, more similar groups to increase homogeneity (Hedges & Olkin, 1986). This method is not ideal because to achieve homogeneity, the final groups no longer represent the whole field, and often they are so small that they do not merit a meta-analysis.

We took a different approach that instead accounted for heterogeneity in two ways. First, we used a mixed-effects model. In mixed-effects models, covariates are used to explain a portion of the variability in effect sizes. We considered a wide variety of covariates, which are addressed in the following sections. Additionally, in mixed models any residual heterogeneity is modeled via random effects, which here account for the variability in true effect sizes. Mixed models are used when there is reason to suspect that variability among effect sizes is not due solely to sampling error (Lipsey & Wilson, 2001).

Second, we used a model that accounted for the nested nature of research studies from the same article. Effect sizes from the same study or article are likely to be similar in many ways. For example, they often share similar study protocols, and the participants are often recruited from the same populations, such as an introductory psychology participant pool at a university. Consequently, effect sizes from the same study or article can be more similar to one another than effect sizes from different studies. In fact, effect sizes can sometimes be construed as having a nested or hierarchical structure; effect sizes are nested within studies, which are nested within articles, and (perhaps) within authors (Hedges, Tipton, & Johnson, 2010a, 2010b; Lipsey & Wilson, 2001). The nested nature of the effect sizes was important to our meta-analysis because although there are a total of 1,038 effect sizes, these effect sizes are nested within 206 studies.

Addressing the Nested Structure of Effect Sizes

In the past, analyzing the nested structure of effect sizes has been difficult. Some researchers have ignored the hierarchical nature of the effect sizes and treated them as if they were independent. However, this carries the substantial risk of inflating the significance of statistical tests because it treats each effect size as contributing one unique degree of freedom when in fact the degrees of freedom at different levels of the hierarchy are not unique. Other researchers have averaged or selected at random effect sizes from particular studies, but this approach disregards a great deal of potentially useful information (see Lipsey & Wilson, 2001, for a discussion of both approaches).

More generally, the problem of nested or multilevel data has been addressed via hierarchical linear modeling (HLM; Raudenbush & Bryk, 2002). Methods for applying HLM theory and estimation techniques to meta-analysis have been developed over the last 25 years (Jackson, Riley, & White, 2011; Kalaian & Raudenbush, 1996; Konstantopoulos, 2011). A shortcoming of these methods, however, is that they can be technically difficult to specify and implement, and can be sensitive to misspecification. This might occur if, for example, a level of nesting had been mistakenly left out, the weights were incorrectly calculated, or the normality assumptions were violated. A new method for robust estimation was recently introduced by Hedges et al. (2010a, 2010b). This method uses an empirical estimate of the sampling variance that is robust to both misspecification of the weights and to distributional assumptions, and is simple to implement, with freely available, open-source software. Importantly, when the same weights are used, the HLM and robust estimation methods generally give similar estimates of the regression coefficients.

In addition to modeling the hierarchical nature of effect sizes, using a hierarchical meta-regression approach is beneficial because it allows the variation in effect sizes to be divided into two parts: the variation of effect sizes within studies and the variation of study–average effect sizes between or across studies. The same distinction can be made for the effect of a particular covariate on the effect sizes. The within-study effect for a covariate is the pooled within-study correlation between the covariate and the effect sizes. The between-study effect is the correlation between the average value of the covariate in a study with the average study effect size. Note that in traditional nonnested meta-analyses, only the between-study variation or regression effects are estimable.

Parsing variation into within- and between-study effects is important for two reasons. First, by dividing analyses into these separate parts, we were able to see which protocols (e.g., age, dependent variable) are commonly varied or kept constant within studies. Second, when the values of a covariate vary within a study, the within effect estimate can be thought of as the effect of the covariate controlling for other unmeasured study or research group variables. In many cases, this is a better measure of the relationship between the covariate of interest and the effect sizes than with the between effect alone.

To illustrate the difference between these two types of effects, imagine two meta-analyses. In the first, every study has both child and adult respondents. This means that within each study, the outcomes for children and adults can be compared by holding constant study or research group variables. This is an example of a within metaregression, which naturally controls for unmeasured covariates within the studies. In the second meta-analysis, none of the studies has both children and adults as respondents. Instead (as is often true in the present meta-analysis), some studies include only children, and others include only adults. The only way that the effect of age can be addressed here is through a comparison across studies, which is a between meta-regression model. In such a model, it would be difficult to determine if any effects of age found were a result of actual differences between age groups or of confounds such as systematic differences in the selection criteria or protocols used in studies with children and studies with adults. In the present meta-analysis, we were sometimes able to gain unique insight into sources of variation in effect sizes by considering the contribution of within- and between-study variance.

Characteristics of the Training Programs

Spatial skills might respond differently to different kinds of training. To investigate this issue, we divided the training program of each study into one of three mutually exclusive categories: (a) those that used video games to administer training, (b) those that used a semester-long or instructional course, and (c) those that trained participants on spatial tasks through practice, strategic instruction, or computerized lessons, often administered in a psychology laboratory. As shown in Table 2, these training categories are similar to Baenninger and Newcombe's (1989) categories. Out of our three categories, course and video game training correspond to what these authors referred to as *indirect* training. We chose to distinguish these two forms of training because of the recent increase in the availability of, and interest in, video game training of spatial abilities (e.g., Green & Bavelier, 2003). Our third category, spatial task training, involved direct practice or rehearsal (what Baenninger and Newcombe termed *specific* training).

Missing Elements From This Meta-Analysis

This meta-analysis provides a comprehensive review of work on the malleability of spatial cognition. Nevertheless, it does not address every interesting question related to this topic. Many such questions one might ask are simply so fine-grained that were we to attempt analyses to answer them, the sample sizes of relevant studies would become unacceptably small. For example, it would be nice to know whether men's and women's responsiveness to training differs for each type of skills that we have identified, or how conclusions about age differences in responsiveness to training are affected by study design. However, these kinds of interaction hypotheses could not be evaluated with the present data set, given the number of effect sizes available. Additionally, the lack of studies that directly assess the effects of spatial training on performance in a STEM discipline is disappointing. To properly measure spatial training's effect on STEM outcomes, we must move away from anecdotal evidence and conduct rigorous experiments testing its effect. Nonetheless, the present study

Table 2
Defining Characteristics of Training Categories and Their Correspondence to the Training Categories Used by Baenninger and Newcombe (1989)

Type of training	Description	Baenninger & Newcombe (1989)
Video game training	Video game used during treatment to improve spatial reasoning	Indirect training
Course training	Semester-long spatially relevant course used to improve spatial reasoning	Indirect training
Spatial task training	Training uses spatial task to improve spatial reasoning	Specific training

provides important information about whether and how training can affect spatial cognition.

Method

Eligibility Criteria

Several criteria were used to determine whether to include a study.

1. The study must have included at least one spatial outcome measure. Examples include, but are not limited to, performance on published psychometric subtests of spatial ability, reaction time on a spatial task (e.g., mental rotation or finding an embedded figure), or measures of environmental learning (e.g., navigating a maze).[1]

2. The study must have used training, education, or another type of intervention that was designed to improve performance on a spatial task.

3. The study must have employed a rigorous, causally relevant design, defined as meeting at least one of the following design criteria: (a) use of a pretest, posttest design that assessed performance relative to a baseline measure obtained before the intervention was given; (b) inclusion of a control or comparison group; or (c) a quasi-experiment, such as the comparison of growth in spatial skills among engineering and liberal arts students.

4. The study must have focused on a nonclinical population. For example, we excluded studies that used spatial training to improve spatial skills after brain injury or in Alzheimer's disease. We also excluded studies that focused exclusively on the rehabilitation of high-risk or at-risk populations.

Literature Search and Retrieval

We began with electronic searches of the PsycINFO, ProQuest, and ERIC databases. We searched for all available records from January 1, 1984, through March 4, 2009 (the day the search was done). We chose this 25-year window for two reasons. First, it was large enough to provide a wide range of studies and to cover the large increase in studies that has occurred recently. Second, the window was small enough to allow us to gather most of the relevant published and unpublished data. The search included foreign language articles if they included an English abstract.

We used the following search term: *(training OR practice OR education OR "experience in" OR "experience with" OR "experience of" OR instruction) AND ("spatial relation" OR "spatial relations" OR "spatial orientation" OR "spatial ability" OR "spatial abilities" OR "spatial task" OR "spatial tasks" OR visuospatial OR geospatial OR "spatial visualization" OR "mental rotation" OR "water-level" OR "embedded figures" OR "horizontality")*. After the removal of studies performed on nonhuman subjects, the search yielded 2,545 hits. The process of winnowing these 2,545 articles proceeded in three steps to ensure that each article met all inclusion criteria (see Figure 2).

Step 1 was designed to eliminate quickly those articles that focused primarily on clinical populations or that did not include a behavioral measure, and involved two raters (postgraduate-level research coordinators and authors of this article) reading only the titles of the articles. Articles were excluded if the title revealed a focus on atypical human populations, including at-risk or low-achieving populations, or disordered populations (e.g., individuals with Parkinson's, HIV, Alzheimer's, genetic disorder, or mental disorders). Also excluded were studies that did not include a behavioral measure, such as studies that only included physiological or cellular activity. Finally, we excluded articles that did not present original data, such as review articles. We instructed the raters to be inclusive in this first step of the winnowing process. For example, if the title of an article did not include sufficient information to warrant exclusion, raters were instructed to leave it in the sample. In addition, we only eliminated an article at this step if both raters agreed that it should be eliminated. Overall, rater agreement was very good (82%). Of the 2,545 articles, 649 were excluded at Step 1. In addition, we found that 244 studies were duplicated, so we deleted one of the copies of each. In total, 1,652 studies survived Step 1.

In Step 2, three raters, the same two authors and an incoming graduate student, read the abstracts of all articles that survived Step 1. The goal of Step 2 was to determine whether the articles included training measures and whether they utilized appropriately rigorous (experimental or quasi-experimental) designs. To train the raters, we asked all three first to read the same 25% (413) of the abstracts. After discussion, interrater agreement was very good (87%, Fleiss's κ = .78). The remaining 75% of articles (1,239) were then divided into three groups, and each of these abstracts was read by two of the three

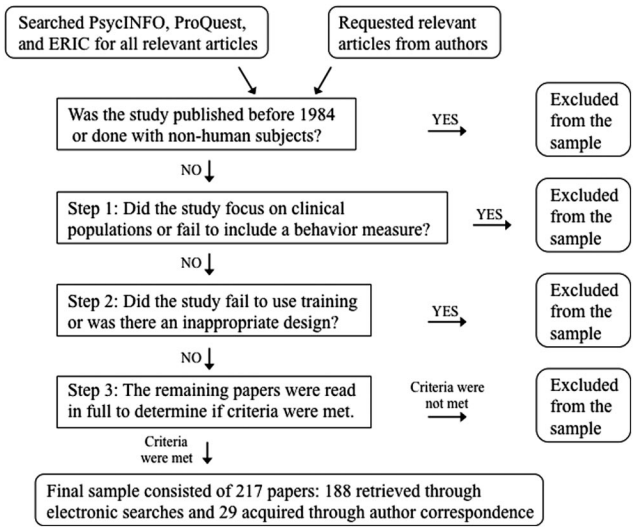

Figure 2. Flowchart illustrating the search and winnowing process for acquiring articles.

[1] Cases in which the training outcome was a single summary score from an entire psychometric test (e.g., Wechsler Preschool and Primary Scale of Intelligence–Revised or the Kit of Factor-Referenced Tests) and provided no breakdown of the subtests were excluded. We were concerned that the high internal consistency of standardized test batteries would inflate improvement, overstating the malleability of spatial skills. Therefore this exclusion is a conservative approach to analyzing the malleability of spatial skills, and ensures that any effects found are not due to this confound.

raters. Interrater agreement among the three pairs of raters was high (84%, 90%, and 88%), and all disagreements were resolved by the third rater. In total, 284 articles survived Step 2.

In Step 3, the remaining articles were read in full. We were unable to obtain seven articles. After reading the articles, we rejected 89, leaving us with 188 articles that met the criteria for inclusion. The level of agreement among raters reading articles in full was good (87%). The Cohen's kappa was .74, which is typically defined as in the "substantial" to "excellent" range (Banerjee, Capozzoli, McSweeney, & Sinha, 1999; Landis & Koch, 1977). The sample included articles written in several non-English languages, including Chinese, Dutch, French, German, Italian, Japanese, Korean, Romanian, and Spanish. Bilingual individuals who were familiar with psychology translated the articles.

We also acquired relevant articles through directly contacting experts in the field. We contacted 150 authors in the field of spatial learning. We received 48 replies, many with multiple suggestions for articles. Reading through the authors' suggestions led to the discovery of 29 additional articles. Twenty-four of these articles were published in scientific journals or institutional technical reports, and five were unpublished manuscripts or dissertations.

Thus, through both electronic search and communication with researchers, we acquired and reviewed data from 217 articles (188 from electronic searches and 29 from correspondence).

Publication bias. Studies reporting large effects are more likely to be published than those reporting small or null effects (Rosenthal, 1979). We made efforts both to attenuate and to assess the effects of publication bias on our sample and analyses. First, when we wrote to authors and experts, we explicitly asked them to include unpublished work. Second, we searched reference lists of our articles for relevant unpublished conference proceedings, and we also looked through the tables of contents of any recent relevant conference proceedings that were accessible online. Third, our search of ProQuest Dissertations and Theses yielded many unpublished dissertations, which we included when relevant. If a dissertation was eventually published, we examined both the published article and the original dissertation. We augmented the data from the published article if the dissertation provided additional, relevant data. However, we only counted the original dissertation and published article as one (published) study.

We also contacted authors when their articles did not provide sufficient information for calculating effect sizes. For example, we requested separate means for control and treatment groups when only the overall group F or t statistics were reported. Authors responded with usable data in approximately 20% of these cases. We used these data to compute effect sizes separately for males and females and control and treatment groups whenever possible.

Coding of Study Descriptors

We coded the methods and procedures used in each study, focusing on factors that might shed light on the variability in the effect sizes that we observed. The coding scheme addressed the following characteristics of each study: the publication status, the study design, control group design and characteristics, the type of training administered, the spatial skill trained and tested, characteristics of the sample, and details about the procedure such as the length of delay between the end of training and the posttest. We have provided the full description of the coding procedure in Appendix A. The majority of these characteristics were straightforward to code. Here we discuss in detail two aspects of the coding that are new to the field: the classification of spatial skills based on the 2×2 framework and how it relates to the coding of transfer of training.

The 2 × 2 framework of spatial skills. We coded each training intervention and outcome measure in terms of both the intrinsic–extrinsic and static–dynamic dimensions. These dimensions are also discussed above in the introduction; here we focus on the defining characteristics and typical tasks associated with each dimension.

Intrinsic versus extrinsic. Spatial activities that involved defining an object were coded as intrinsic. Identifying the distinguishing characteristics of a single object, for example in the Embedded Figures Task, the Paper Folding Task, and the Mental Rotations Test, is an intrinsic process because the task requires only contemplation of the object at hand, without consideration of the object's surroundings.

In contrast, spatial activities that required the participant to determine relations among objects in a group, relative to one another or to an overall framework, were coded as extrinsic. Classic examples of extrinsic activities are the Water-Level Task and Piaget's Three Mountain Task, as both tasks require the participant to understand how multiple items relate spatially to one another.

Static versus dynamic. Spatial activities in which the main object remains stationary were coded as static. For example, in the Embedded Figures Task and the Water-Level Task, the object at hand does not change in orientation, location, or dimension. The main object remains static to the participant throughout the task.

In contrast, spatial activities in which the main object moves, either physically or in the mind of the participant, were coded as dynamic. For example, in the Paper Folding Task, the presented object must be contorted and altered to create the three-dimensional answer. Similarly, in the Mental Rotations Test and Piaget's Three Mountain Task, the participant must rotate either the object or his or her own perspective to determine which suggested orientation aligns with the original. These processes require dynamic interaction with the stimulus.

Transfer. To analyze transfer of training, we coded both the training task and all outcome measures into a single cell of the 2×2 framework (intrinsic and static, or intrinsic and dynamic, etc.).[2] We used the framework to define two levels of transfer. Within-cell transfer was coded when the training and outcome measure were (a) not the same but (b) both in the same cell of the 2×2 framework. Across-cell transfer was coded when the training and outcome measures were in different cells of the 2×2 framework.

Computing Effect Sizes

The data from each study were entered into the computer program Comprehensive Meta-Analysis (CMA; Borenstein, Hedges, Higgins, & Rothstein, 2005). CMA provides a well-organized and efficient format for conducting and analyzing meta-

[2] In some cases training could not be classified into a 2×2 cell; for example, in studies that used experience in athletics as training (Guillot & Collet, 2004; Ozel, Larue, & Molinaro, 2002). Experiments such as these were not included in the analyses of transfer within and across cells of the 2×2 framework.

analytic data (the CMA procedures for converting raw scores into effect sizes can be found in Appendix B).

Measures of effect size typically quantify the magnitude of gain associated with a particular treatment relative to the improvement observed in a relevant control group (Morris, 2008). Gains can be conceptualized as an improvement in score. Effect sizes are usually computed from means and standard deviations, but they can also be computed from an F statistic, t statistic, or chi-square value as well as from change scores representing the difference in mean performance at two points in time. Thus, in some cases, it was possible to obtain effect sizes without having the actual mean scores associated with a treatment (see Hunter & Schmidt, 2004; Lipsey & Wilson, 2001). All effect sizes were expressed as Hedges's g, a slightly more conservative derivative of Cohen's d (J. Cohen, 1992); Hedges's g includes a correction for biases due to sample size.

To address the general question of the degree of malleability of spatial skills, we calculated an overall effect size for each study (the individual effect sizes are reported in Appendix C). The definition of the overall effect size depended in part on the design of the study. As discussed above, the majority of studies used a mixed design, in which performance was measured both before (pretest) and after (posttest) training, in both a treatment and control group. In this case, the overall effect size was the difference between the improvement in the treatment group and the improvement in the control group. Other studies used a between-only design, in which treatment and control groups were tested only after training. In this case, the overall effect size represented the difference between the treatment and control groups. Finally, approximately 15% of the studies used a within-subjects-only design, in which there is no control or comparison group and performance is assessed before and after training. In this case, the overall effect size was the difference between the posttest and pretest. We combined the effect sizes from the different designs to generate an overall measure of malleability. However, we also considered the effects of differences in study design and of improvement in control groups in our analysis of moderators.

Implementing the Hedges et al. (2010a, 2010b) Robust Estimation Model

As noted above, we implemented the Hedges et al. (2010a, 2010b) robust variance estimation model to address the nested nature of effect sizes. We conducted these analyses in R (Hornik, 2011) using the function robust.hier.se (http://www.northwestern.edu/ipr/qcenter/RVE-meta-analysis.html) with inverse variance weights and, when confidence intervals and p values are reported, using a t distribution with m-p degrees of freedom, where m is the number of studies and p is the number of predictors in the model.

More formally, the model we used for estimation was

$$T_{ij} = \mathbf{X_{ij}}\boldsymbol{\beta} + \theta_i + \eta_{ij} + \epsilon_{ij},$$

where T_{ij} is the estimated effect size from outcome j in study i, $\mathbf{X_{ij}}$ is the design matrix for effect sizes in study j, β is a $p \times 1$ vector of regression coefficients, θ_i is a study-level random effect, η_{ij} is a within-study random effect, and ϵ_{ij} is the sampling error. This is a mixed or meta-regression model. It seeks both to explain variation in effect sizes via the covariates in $\mathbf{X_{ij}}$ and to account for unexplained variation via the random effects terms θ_i, η_{ij}, and ϵ_{ij}. In all the analyses provided here, we assume that the regression coefficients in β are fixed. The covariates in $\mathbf{X_{ij}}$ include, for instance, an intercept (giving the average effect), dummy variables (when categorical covariates like "type of training" are of interest), and continuous variables.

With this model, the residual variation of the effect size estimate T_{ij} can be decomposed as

$$V(T_{ij}) = \tau^2 + \omega^2 + \nu_{ij},$$

where τ^2 is the variance of the between-study residuals θ_i, ω^2 is the variance of the within-study residuals η_{ij}, and ν_{ij} is the known sampling variance of the residuals ϵ_{ij}. This means that there are three sources of variation in the effect size estimates. Although we assume that ν_{ij} is known, we estimate both τ^2 and ω^2 using the estimators provided in Hedges et al. (2010b). In all the results shown here, each effect size was weighted by the inverse of its variance, which gives greater weight to more precise effect size estimates.

Our method controls for heterogeneity without reducing the sample to an inconsequential size. Importantly, this approach also provides a robust standard error for each estimate of interest; the size of the standard error is affected by the number of studies (m), the sampling variance within each study (ν_{ij}), and the degree of heterogeneity (τ^2 and ω^2). This means that when there is a large degree of heterogeneity (τ^2 or ω^2), estimates of the average effect sizes will be more uncertain, and our statistical tests took this uncertainty into account.

Finally, all analyses presented here were estimated with a mixed model approach. In some cases, the design matrix only included a vector of 1s; in those cases only the average effect is estimated. In other cases, comparisons between levels of a factor were compared (e.g., posttest delays of 1 day, less than 1 week, and less than 1 month to test durability of training); in those cases the categorical factor with k levels was converted into $k - 1$ dummy variables. In a few models we included continuous covariates in the design matrix. In these cases, we centered the within-study values of the covariate around the study–average, enabling the estimation of separate within- and between-study effects. Finally, for each outcome or comparison of interest, following the standard protocol for the robust estimation method used, we present the estimate and p value. We do not present information on the degree of residual heterogeneity unless it answers a direct question of interest.

Results

We begin by reporting characteristics of our sample, including the presence of outliers and publication bias. Next, we address the overall question of the degree of malleability of spatial skills and whether training endures and transfers. We then report analysis of several moderators.

Characteristics of the Sample of Effect Sizes

Outliers. Twelve studies reported very high individual effect sizes, with some as large as 8.33. The most notable commonality among these outliers was that they were conducted in Bahrain, Malaysia, Turkey, China, India, and Nigeria; countries that, at the

time of analysis, were ranked 39, 66, 79, 92, 134, and 158, respectively, on the Human Development Index (HDI). The HDI is a composite of standard of living, life expectancy, well-being, and education that provides a general indicator of a nation's quality of life and socioeconomic status (United Nations Development Programme, 2009).[3] For studies with an HDI over 30, the mean effect size (g = 1.63, SE = 0.44, m = 12, k = 114) was more than 3 times the group mean of the remaining sample (g = 0.47, SE = 0.04, m = 206, k = 1,038), where m represents the number of studies and k represents the total number of effect sizes. Prior research has found that lower socioeconomic status is associated with larger responses to training or interventions (Ghafoori & Tracz, 2001; Wilson & Lipsey, 2007; Wilson, Lipsey, & Derzon, 2003). The same was true in these data: There was a significant correlation between HDI ranking and effect size (ρ = .35, p < .001), with the higher rankings (indicating lower standards of living) correlated with larger effect sizes. Because inclusion of these outliers could distort the main analyses, these 12 studies were not considered further.[4]

Assessing publication bias. Although we performed a thorough search for unpublished studies, publication bias is always possible in any meta-analysis (Lipsey & Wilson, 1993). Efforts to obtain unpublished studies typically reduce but do not eliminate the "file drawer" problem (Rosenthal, 1979). We evaluated whether publication bias affected our results in several ways. First, we compared the average effect size of published studies (g = 0.56, SE = 0.05, m = 95, k = 494) and unpublished studies (g = 0.39, SE = 0.06, m = 111, k = 544) in our sample. The difference was significant at p < .05. This result indicates that there is some publication bias in our sample and raises the concern that there could be more unpublished or inaccessible studies that, if included, would render our results negligible (Orwin, 1983) or trivial (Hyde & Linn, 2006). We therefore calculated the fail-safe N (Orwin, 1983) to determine how many unpublished studies averaging no effect of training (g = 0) would need to exist to lower our mean effect size to trivial levels. Orwin (1983) defined the fail-safe N as follows: $N_{fs} = N_0[(d_0 - d_c)/d_c]$, with N_{fs} as the fail-safe N, N_0 as the number of studies, d_0 as the overall effect size, and d_c as the set value for a negligible effect size. If we adopted Hyde and Linn's (2006) value of 0.10 as a trivial effect size, it would take 762 studies with effect sizes of 0 that we overlooked to reduce our results to trivial. If we adopted a more conservative definition of a negligible effect size, 0.20, there would still need to be 278 overlooked studies reporting an effect size of 0 to reduce our results to negligible levels. Finally, we also created a funnel plot of the results to provide a visual measure of publication bias. Figure 3 shows the funnel plot of each study's mean weighted effect size versus its corresponding standard error. The mostly symmetrical placement of effect sizes in the funnel plot, along with the large fail-safe N calculated above, indicate that although there was some publication bias in our sample, it seems very unlikely that the major results are due largely to publication bias.

Characteristics of the trimmed sample. Our final sample consisted of 206 studies with 1,038 effect sizes. The relatively large ratio of effect sizes to studies stems from our goal of analyzing the effects of moderators such as sex and the influence of different measures of spatial skills. Whenever possible, we separated the published means by gender, and when different means for different dependent variables were given, we calculated all potential effect sizes for each. Overall, 95 studies (46%) were published in journals, and 111 (54%) were from (unpublished) dissertations, unpublished data, or conference articles; 163 studies (79%) were conducted in the United States. The characteristics of the sample are summarized in Table 3.

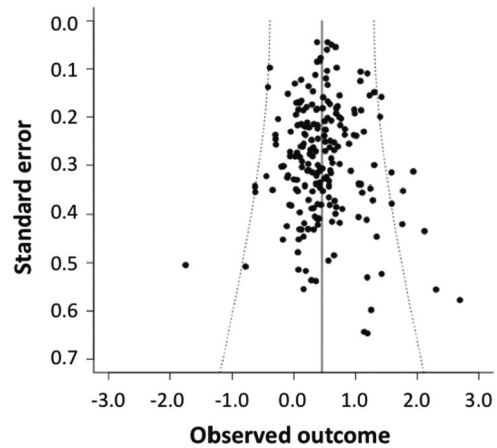

Figure 3. Funnel plot of each study's mean weighted effect size by study–average variances to measure for publication bias. The funnel indicates the 95% random-effects confidence interval.

Assessing the Malleability of Spatial Skills

We now turn to the main question of this meta-analysis: How malleable are spatial skills? Excluding outliers, the overall mean weighted effect size relative to available controls was 0.47 (SE = 0.04, m = 206, k = 1,038). This result includes all studies regardless of research design, and suggests that, in general, spatial skills are moderately malleable. Spatial training, on average, improved performance by almost one half a standard deviation.

Assessing and addressing heterogeneity. It is important to consider not only the average weighted effect size but also the degree of heterogeneity of these effect sizes. By definition, a mixed-effects meta-analysis does not assume that each study represents the same underlying effect size, and hence some degree of

[3] For the analyses involving the HDI, the rankings for each country were taken from the *Human Development Report 2009* (United Nations Development Programme, 2009). The 2009 HDI ranking goes from 1 (*best*) to 182 (*worst*) and is created by combining indicators of life expectancy, educational attainment, and income. Norway had an HDI ranking of 1, Niger had an HDI ranking of 182, and the United States had an HDI of 13. HDI rankings were first published in 1990, and therefore it was not possible to get the HDI at the time of publication for each article. Therefore to be consistent, we used the 2009 (year the analyses were performed) HDI rankings to correlate with the magnitude of the effect sizes.

[4] The studies that we excluded were Gyanani and Pahuja (1995, India); Li (2000, China); Mshelia (1985, Nigeria); Rafi, Samsudin, and Said (2008, Malaysia); Seddon, Eniaiyeju, and Jusoh (1984, Nigeria); Seddon and Shubber (1984, Bahrain); Seddon and Shubber (1985a, 1985b, Bahrain); Shubbar (1990, Bahrain); G. G. Smith et al. (2009, Turkey); Sridevi, Sitamma, and Krishna-Rao (1995, India); and Xuqun and Zhiliang (2002, China).

Table 3
Characteristics of the 206 Studies Included in the Meta-Analysis After the Exclusion of Outliers

Coded variable	*n* (studies)	% of studies
Participant characteristics		
Gender composition		
All male	10	5
All female	18	9
Both male and female	48	24
Not specified[a]	130	62
Age of participants in years[b]		
Younger than 13	53	26
13–18 (inclusive)	39	19
Older than 18	118	57
Study methods and procedures		
Study design[b]		
Mixed design	123	59
Between subjects	55	27
Within subjects only	31	15
Days from end of training to posttest[b]		
None (immediate posttest)	137	67
1–6	17	8
7–31	37	18
More than 31	4	1
Transfer[b]		
No transfer	45	22
Transfer within 2 × 2 cell	94	46
Transfer across 2 × 2 cells	51	25
2 × 2 spatial skill cells as outcome measures[b]		
Intrinsic, static	52	25
Intrinsic, dynamic	189	92
Extrinsic, static	14	6
Extrinsic, dynamic	15	7
Training categories		
Video games	24	12
Courses	42	21
Spatial task training	138	67
Prescreened to include only low scorers	19	9
Study characteristics		
Published	95	46
Publication year (for all articles)		
1980s	55	27
1990s	93	45
2000s	58	28
Location of study[b]		
Australia	2	1
Austria	1	1
Canada	14	7
France	2	1
Germany	5	2
Greece	1	1
Israel	1	1
Italy	3	1
Korea	6	3
Norway	1	1
Spain	4	2
Taiwan, Republic of China	2	1
The Netherlands	2	1
United Kingdom	1	1
United States	163	79

[a] Data were not reported in a way that separate effect sizes could be obtained for each sex. [b] Percentages do not sum to 100% because of studies that tested multiple age groups, used multiple study designs, used life experience as the intervention, included outcome measures from multiple cells of the 2 × 2, or tested participants from more than one country.

heterogeneity is expected. But how much was there, and how does this affect our interpretation of the results?

An important contribution of this meta-analysis is the separation of heterogeneity into variability across studies (τ^2) and within studies (ω^2), following the method of Hedges et al. (2010a, 2010b). The between-studies variability, τ^2, was estimated to be 0.185, and the within-studies variability, ω^2, was estimated to be 0.025. These estimates tell us that effect sizes from different studies varied from one another much more than effect sizes from the same study. It is not surprising that we found greater heterogeneity in effect sizes between studies than in effect sizes that come from the same study, given that studies differ from each other in many ways (e.g., types of training and measures used, variability in how training is administered, participant demographic characteristics).

As discussed in the Method section, the statistical procedures that we used throughout this article take both sources of heterogeneity into account when estimating the significance of a given effect. In all subsequent analyses, we took both between- and within-study heterogeneity into account when calculating the statistical significance of our findings. Our statistical tests are thus particularly conservative.

Durability of training. We have already demonstrated that spatial skills respond to training. It is also very important to consider whether the effects of training are fleeting or enduring. To address this question, we coded the time delay from the end of training until the posttest was administered for each study. Some researchers administered the posttest immediately; some waited a couple of days, some waited weeks, and a few waited over a month. When posttests administered immediately after training were compared with all posttests that were delayed, collapsing across the delayed posttest time intervals did not show a significant difference ($p > .67$). There were no significant differences between immediate posttest, less than 1 week delay, and less than 1 month delay ($p > .19$). Because only four studies involved a delay of more than 1 month, we did not include this category in our analysis. The similar magnitude of the mean weighted effect sizes produced across the distinct time intervals implies that improvement gained from training can be durable.

Transferability of training. The results thus far indicate that training can be effective and that these effects can endure. However, it is also critical to consider whether the effects of training can transfer to novel tasks. If the effects of training are confined to performance on tasks directly involved in the training procedure, it is unlikely that training spatial skills will lead to generalized performance improvements in the STEM disciplines. We approached this issue in two overlapping ways. First, we asked whether there was any evidence of transfer. We separated the studies into those that attempted transfer and those that did not to allow for an overall comparison. For this initial analysis, we considered all studies that reported any information about transfer (i.e., all studies except those coded as "no transfer"). We found an effect size of 0.48 ($SE = 0.04$, $m = 170$, $k = 764$), indicating that training led to improvement of almost one half a standard deviation on transfer tasks.

Second, we assessed the degree or range of transfer. How much did training in one kind of task transfer to other kinds of tasks? As noted above, we used our 2 × 2 theoretical framework to distinguish within-cell transfer from across-cell transfer, with the latter

representing transfer between a training task and a substantially different transfer task. Interestingly, the effect sizes for transfer within cells of the 2 × 2 ($g = 0.51$, $SE = 0.05$, $m = 94$, $k = 448$) and those for transfer across cells ($g = 0.55$, $SE = 0.10$, $m = 51$, $k = 175$) both differed significantly from 0 ($p < .01$). Thus, for the studies that tested transfer, there was strong evidence of not only within-cell transfer involving similar training and transfer tasks, but also of across-cell transfer in which the training and transfer tasks might be expected to tap or require different skills or representations.

Moderator Analyses

The overall finding of almost one half a standard deviation improvement for trained spatial skills raises the question of why there has been such variability in prior findings. Why have some studies failed to find that spatial training works? To investigate this issue, we examined the influences of several moderators that could have produced this variability in the results of studies. Table 4 presents a list of those moderators and the results of the corresponding analyses.

Table 4
Summary of the Moderators Considered and Corresponding Results

Variable	*g*	*SE*	*m*	*k*
Malleability of spatial skills				
Malleable				
Overall	0.47	0.04	206	1,038
Treatment only	0.62	0.04	106	365_a
Control only	0.45	0.04	106	372_b
Durable				
Immediate posttest	0.48	0.05	137	611
Delayed posttest	0.44	0.08	65	384
Transferable				
No transfer	0.45	0.09	45	272
Within 2 × 2 cell	0.51	0.05	94	448
Across 2 × 2 cell	0.55	0.10	51	175
Study design				
Within subjects	0.75	0.08	31	160_e
Between subjects	0.43	0.09	55	304
Mixed	0.40	0.05	123	574
Control group activity				
Retesting effect				
Pretest/posttest on a single test	0.33	0.04	34	111_a
Repeated practice	0.75	0.17	7	27_b
Pretest/posttest on spatial battery	0.46	0.07	34	109
Pretest/posttest on nonspatial battery	0.40	0.11	9	36
Spatial filler				
Spatial filler (control group)	0.51	0.06	49	160
Nonspatial filler (control group)	0.37	0.05	46	159
Overall for spatial filler controls	0.33	0.05	70	315_a
Overall for nonspatial filler controls	0.56	0.06	69	309_b
Type of training				
Course	0.41	0.11	42	154
Video games	0.54	0.12	24	89
Spatial task	0.48	0.05	138	786
Sex				
Male improvement	0.54	0.08	63	236
Female Improvement	0.53	0.06	69	250
Age				
Children	0.61	0.09	53	226
Adolescents	0.44	0.06	39	158
Adults	0.44	0.05	118	654
Initial level of performance				
Studies that used only low-scoring subjects	0.68	0.09	19	169_a
Studies that did not separate subjects	0.44	0.04	187	869_b
Accuracy versus response time				
Accuracy	0.31	0.14	99	347_c
Response time	0.69	0.14	15	41_d
2 × 2 spatial skills outcomes[a]				
Intrinsic, static	0.32	0.10	52	166
Intrinsic, dynamic	0.44	0.05	189	637
Extrinsic, static	0.69	0.10	14	148
Extrinsic, dynamic	0.49	0.13	15	45

Note. Subscripts a and b indicate the two groups differ at $p < .01$; subscripts c and d indicate the two groups differ at $p < .05$; subscript e indicates group differs at $p < .01$ from all other groups.
[a] All categories differed from 0 ($p < .01$).

Study design. As previously noted, there were three kinds of study designs: within subjects only, between subjects, and mixed. Fifteen percent of studies in our sample used the within-subjects design, 26% used the between-subjects design, and the remaining 59% of the studies used the mixed design. We analyzed differences in overall effect size as a function of design type. In this and all subsequent post hoc contrasts, we set alpha at .01 to reduce the Type I error rate. The difference between design types was significant ($p < .01$). As expected, studies that used a within-subjects-only design, which confounds training and retesting effects, reported the highest overall effect size ($g = 0.75$, $SE = 0.08$, $m = 31$, $k = 160$). The within-subjects-only mean weighted effect size significantly exceeded those for both the between-subjects ($g = 0.43$, $SE = 0.09$, $m = 55$, $k = 304$, $p < .01$) and mixed design studies ($g = 0.40$, $SE = 0.05$, $m = 123$, $k = 574$, $p < .01$). The mean weighted effect sizes for the between-subjects and mixed designs did not differ significantly. These results imply that the presence or absence of a control group clearly affects the magnitude of the resulting effect size, and that studies without a control group will tend to report higher effect sizes.

Control group effects. Why, and how, do control groups have such a profound effect on the size of the training effect? To investigate these questions, we analyzed control group improvements separately from treatment group improvements. This analysis was only possible for the mixed design studies, as the within and between designs do not include a control group or a measure of control group improvement, respectively. We were unable to separate the treatment and control means for approximately 15% of the mixed design studies because of insufficient information provided in the article and lack of response from authors to our requests for the missing information. The mean weighted effect size for the control groups ($g = 0.45$, $SE = 0.04$, $m = 106$, $k = 372$) was significantly smaller than that for the treatment groups ($g = 0.62$, $SE = 0.04$, $m = 106$, $k = 365$, $p < .01$).

Two potentially important differences between control groups can be the number of times a participant takes a test and the number of tests a participant takes. If the retesting effect can appear within a single pretest and posttest as discussed above, it stands to reason that retesting or multiple distinct tests could generate additional gains. In some studies, control groups were tested only once (e.g., Basham, 2006), whereas in other studies they were tested multiple times (e.g., Heil, Roesler, Link, & Bajric, 1998). To measure the extent of retesting effects on the control group effect sizes, we coded the control group designs into four categories: (a) pretest and posttest on a single test, (b) pretest then retest then posttest on a single test (i.e., repeated practice), (c) pretest and posttest on several different spatial tests (i.e., a battery of spatial ability tests), and (d) pretest and posttest on a battery of nonspatial tests. As shown in Figure 4, control groups that engaged in repeated practice as their alternate activity produced significantly larger mean weighted effect sizes than those that took a pretest and posttest only ($p < .01$). These results highlight that a control group can improve substantially without formal training if they receive repeated testing.

Filler task content. In addition to retesting effects, control groups can improve through other implicit forms of training. Although by definition control groups do not receive direct training, this does not necessarily mean that the control group did nothing. Many studies included what we will refer to as a *spatial filler* task. These control tasks were designed to determine whether the improvement observed in a treatment group was attributable to a specific kind of training or to simply repeated practice on any form of spatial task. For example, while training was occurring in Feng, Spence, and Pratt's (2007) study, their control participants played the 3-D puzzle video game Ballance. In contrast, other studies used much less spatially demanding tasks as fillers, such as playing Solitaire (De Lisi & Cammarano, 1996). Control groups that received spatial filler tasks produced a larger mean weighted effect size than control groups that received nonspatial filler tasks, with a difference of 0.17. The spatial filler and nonspatial filler control groups did not differ significantly; however, we hypothesized that the large (but nonsignificant) difference between the two could in fact make a substantial difference on the overall effect size. As mentioned above, a high-performing control group can depress the overall effect size reported. Therefore those studies whose control groups received spatial filler tasks may report depressed overall effect sizes because the treatment groups are being compared to a highly improving control group. To investigate this possibility, we compared the overall effect sizes for studies in which the control group received a spatial filler task to studies in which the control received a nonspatial filler task. Studies that used a nonspatial filler control group reported significantly higher effect sizes than studies that used a spatial filler control group ($p < .01$). This finding is a good example of the importance of considering control groups in analyzing overall effect sizes: The larger improvement in the spatial filler control groups actually suppressed the difference between experimental and control groups, leading to the (false) impression that the training was less effective (see Figure 5).

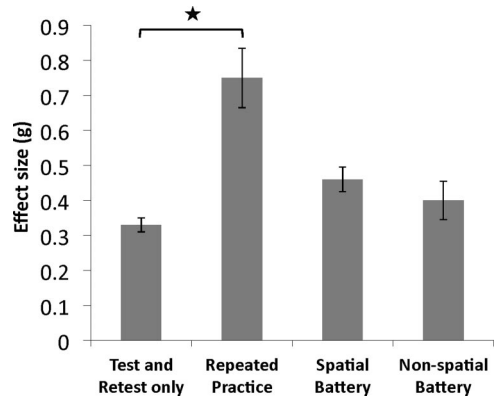

Figure 4. Effect of number of tests taken on the mean weighted effect size within the control group. The error bars represent the standard error of the mean-weighted effect size.

Type of training. In addition to control group effects, one would expect that the type of training participants receive could affect the magnitude of improvement from training. To assess the relative effectiveness of different types of training, we divided the training programs used in each study into three mutually exclusive categories: course, video game, and spatial task training (see Table 2). The mean weighted effect sizes for these categories did not differ significantly ($p > .45$). Interestingly, as implied by our mutually exclusive coding for these training programs, no studies implemented a training protocol

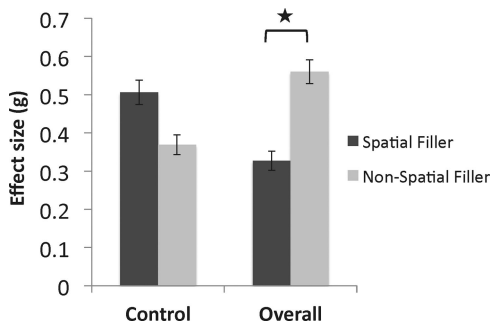

Figure 5. Effect of control group activity on the overall mean weighted effect size produced. The error bars represent the standard error of the mean-weighted effect size.

that included more than one method of training. The fact that these three categories of training did not produce statistically different overall effects largely results from the high degree of heterogeneity for the course ($\tau^2 = 0.207$) and video game ($\tau^2 = 0.248$) training categories. However, overall we can say that each program produced positive improvement in spatial skills, as all three of these methods differed significantly from 0 at $p < .01$.

Participant characteristics. We now turn to moderators involving the characteristics of the participants, including sex, age, and initial level of performance.

Sex. Prior work has shown that males consistently score higher than females on many standardized measures of spatial skills (e.g., Ehrlich, Levine, & Goldin-Meadow, 2006; Geary, Saults, Liu, & Hoard, 2000), with the notable exception of object location memory, in which women sometimes perform better, although the effects for object location memory are extremely variable (Voyer, Postma, Brake, & Imperato-McGinley, 2007). There has been much discussion of the causes of the male advantage, although arguably a more important question is the extent of malleability shown by the two sexes (Newcombe, Mathason, & Terlecki, 2002). Baenninger and Newcombe (1989) found parallel improvement for the training studies in their meta-analysis, so we tested whether this equal improvement with training persisted over the last 25 years.

We first examined whether there were sex differences in the overall level of performance. Forty-eight studies provided both the mean pretest and mean posttest scores for male and female participants separately and thus were included in this analysis. The effect size for this one analysis was not a measure of the effect of training but rather of the difference between the level of performance of males and females at pre- and posttest. A positive Hedges's *g* thus represents a male advantage, and a negative Hedges's *g* represents a female advantage. As expected, males on average outperformed females on the pretest and the posttest in both the control group and the treatment group (see Table 5). All the reported Hedges's *g* statistics in the table are greater than 0, indicating a male advantage.

Next we examined whether males and females responded differently to training. The mean weighted effect sizes for improvement for males were very similar to that of females, with a difference of only 0.01. Thus, males and females improved about the same amount with training. Our findings concur with those of Baenninger and Newcombe (1989) and suggest that although males tend to have an advantage in spatial ability, both genders improve equally well with training.

Age. Generally speaking, children's thinking is thought to be more malleable than adults' (e.g., Heckman & Masterov, 2007; Waddington, 1966). Therefore, one might expect that spatial training would be more effective for younger children than for adolescents and adults. Following Linn and Petersen (1985), we divided age into three categories: younger than 13 years (children), 13–18 years (adolescents), and older than 18 years (adults). Comparing the mean weighted effect sizes of improvement for each age category showed a difference of 0.17 between children and both adolescents and adults. Nevertheless, the difference between the three categories did not reach statistical significance.

An important question is why this difference was not statistically significant. By accounting for the nested nature of the effect sizes, we were able to isolate two important findings here. First, although the estimated difference between age groups is indeed not negligible, the estimate is highly uncertain; and this uncertainty is largely a result of the heterogeneity in the estimates. For example, within the child group, many of the same-aged participants came from different studies, and the mean effect sizes for these studies differed considerably ($\tau^2 = 0.195$). This indicates that the average effect for the child group is not as certain as it would have been if the effect sizes were homogeneous. This nonsignificant finding is a good example of the importance of examining heterogeneity and the nested nature of effect sizes.

The high degree of between study variability reflects the nature of most age comparisons in developmental and educational psychology. Individual studies usually do not include participants of widely different ages. In the present meta-analysis, only four studies included both children (younger than age 13) and adolescents (13–18), and no studies compared children to adults or adolescents to adults. Thus, age comparisons can only be made between studies, and it is difficult to tease apart true developmental differences from differences in factors such as study design and outcome measures. Further studies are needed that compare the multiple age groups in the same study.

Initial level of performance. Some prior work suggests that low-performing individuals may show a different trajectory of improvement with training compared to higher performing individuals (Terlecki, Newcombe, & Little, 2008). Thus, we tested whether training studies that incorporated a screening procedure to identify low scorers yielded higher (or lower) effect sizes compared to those that enrolled all participants, regardless of initial performance level. In all, 19 out of 206 studies used a screening

Table 5
Mean Weighted Effect Sizes Favoring Males for the Sex-Separated Comparisons

	Pretest				Posttest			
Group	*g*	*SE*	*m*	*k*	*g*	*SE*	*m*	*k*
Control	0.29	0.07	29	79[a]	0.24	0.06	29	79[a]
Treatment	0.37	0.08	29	79[a]	0.26	0.05	29	79[a]

[a] $p < .01$ when compared to 0, indicating a male advantage.

procedure to identify and train low scorers. These 19 studies reported significantly larger effects of training ($g = 0.68$, $SE = 0.09$, $m = 19$, $k = 169$) than the remaining 187 studies ($g = 0.44$, $SE = 0.04$, $m = 187$, $k = 869$, $p = .02$), suggesting that focusing on low-scorers instead of testing a random sample can generate a larger magnitude of improvement.

Outcome measures. Our final set of moderators concerned differences in how the effects of training were measured.

Accuracy versus response time. Researchers may use multiple outcome measures to assess spatial skills and responses to training. For example, in mental rotation tasks, researchers can measure both accuracy and response time. We investigated whether the use of these different measures influenced the magnitude of the effect sizes. The analysis of accuracy and response time was performed only for studies that used mental rotation tasks because only these studies consistently measured and reported both. We used Linn and Petersen's definition of mental rotation to isolate the relevant studies. Mental rotation tests such as the Vandenberg and Kuse's Mental Rotations Test (Alington, Leaf, & Monaghan, 1992), Shepard and Metzler (Ozel, Larue, & Molinaro, 2002), and the Card Rotations Test (Deratzou, 2006) were common throughout the literature.

Both response time ($g = 0.69$, $SE = 0.13$, $m = 15$, $k = 41$) and accuracy ($g = 0.31$, $SE = 0.14$, $m = 92$, $k = 305$) improved in response to training. One-sample t tests indicated that the mean effect size differed significantly from 0 ($p < .01$), supporting the malleability of mental rotation tasks established above. Reaction time improved significantly more than accuracy ($p < .05$).

The 2 × 2 spatial skills as outcomes. Finally, we examined whether our 2 × 2 typology of spatial skills can shed light on differences in the malleability of spatial skills. Do different kinds of spatial tasks respond differently to training? Table 4 gives the mean weighted effect sizes for each of the 2 × 2 framework's spatial skill cells. The table reveals that each type of spatial skill is malleable; all the effect sizes differed significantly from 0 ($p < .01$). Extrinsic, static measures produced the largest gains. However, the only significant difference between categories at an alpha of .01 was between extrinsic, static measures and intrinsic, static measures. Note that extrinsic, static measures include the Water-Level Task and the Rod and Frame Task, two tests that ask the participant to apply a learned principle to solve the task. In some cases, teaching participants straightforward rules about the tasks (e.g., draw the line representing the water parallel to the floor) may lead to large improvements, although it is not clear that these improvements always endure (see Liben, 1977). In contrast, intrinsic, static measures may respond much less to training because the researcher cannot tell the participant what particular form to look for. All that can be communicated is the possibility of finding a form, but it is still up to the participant to determine what shape or form is represented. This more general skill may be harder to teach or train. Overall, despite the variety of spatial skills surveyed here in this meta-analysis, our results strongly suggest that performance on spatial tasks unanimously improved with training and the magnitude of training effects was fairly consistent from task to task.

Discussion

This is the first comprehensive and detailed meta-analysis of the effects of spatial training. Table 4 provides a summary of the main results. The results indicate that spatial skills are highly malleable and that training in spatial thinking is effective, durable, and transferable. This conclusion holds true across all the categories of spatial skill that we examined. In addition, our analyses showed that several moderators, most notably the presence or absence of a control group and what the control group did, help to explain the variability of findings. In addition, our novel meta-analytical statistical methods better control for heterogeneity without sacrificing data. We believe that our findings not only shed light on spatial cognition and its development, but also can help guide policy decisions regarding which spatial training programs can be implemented in economically and educationally feasible ways, with particular emphasis on connections to STEM disciplines.

Effectiveness, Durability, and Transfer of Training

We set several criteria for establishing the effectiveness of training and hence the malleability of spatial cognition. The first was simply that training effects should be reliable and at least moderate in size. We found that trained groups showed an average effect size of 0.62, or well over one half a standard deviation in improvement. Even when compared to a control group, the size of this effect was approaching medium (0.47).

The second criterion was that training should lead to durable effects. Although the majority of studies did not include measures of the durability of training, our results indicate that training can be durable. Indeed, the magnitude of training effects was statistically similar for posttests given immediately after training and after a delay from the end of training. Of course, it is possible that those studies that included delayed assessment of training were specifically designed to enhance the effects or durability of training. Thus, further research is needed to specify what types of training are most likely to lead to durable effects. In addition, it is important to note that very few studies have examined training of more than a few weeks' duration. Although such studies are obviously not easy to conduct, they are essential for answering questions regarding the long-term durability of training effects. The third criterion was that training had to be transferable. This was perhaps the most challenging criterion, as the general view has been that spatial training does not transfer or at best leads to only very limited transfer. However, the systematic summary that we have provided suggests that transfer is not only possible, but at least in some cases is not necessarily limited to tasks that very closely resemble the training tasks. For example, Kozhevnikov and Thornton (2006) found that interactive, spatially rich lecture demonstrations of physics material (e.g., Newton's first two laws) generated improvement on a paper-folding posttest. In some cases, the tasks involved different materials, substantial delays, and different conceptual demands, all of which are criteria for meaningful transfers that extend beyond a close coupling between training and assessment (Barnett & Ceci, 2002).

Why did our meta-analysis reveal that transfer is possible when other researchers have argued that transfer is not possible (e.g., NRC, 2006; Sims & Mayer, 2002; Schmidt & Bjork, 1992)? One possibility is that studies that planned to test for transfer were designed in such a way to maximize the likelihood of achieving transfer. Demonstrating transfer often requires intensive training (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). For example, many studies that achieved transfer effects administered large numbers of trials during training (e.g., Lohman & Nichols, 1990), trained participants over a long period (e.g., Terlecki et al.,

2008; Wright et al., 2008), or trained participants to asymptote (Feng et al., 2007). Transfer effects must also be large enough to surpass the test–retest effects observed in control groups (Heil et al., 1998). Thus, although it is true that many studies do not find transfer, our results clearly show that transfer is possible if sufficient training or experience is provided.

Establishing a Spatial Ability Framework

Research on spatial ability needs a unifying approach, and our work contributes to this goal. We took the theoretically motivated 2×2 design outlined in Newcombe and Shipley (in press), deriving from work done by Chatterjee (2008), Palmer (1978), and Talmy (2000), and aligned the preexisting spatial outcome measure categories from the literature with this framework. Comparing this classification to that used in Linn and Petersen's (1985) meta-analysis, we found that their categories mostly fit into the 2×2 design, save one broad category that straddles the static and dynamic cells within the intrinsic dimension. Working from a common theoretical framework will facilitate a more systematic approach to researching the malleability of each category of spatial ability. Our results demonstrate that each category is malleable when compared to 0, although comparisons across categories showed few differences in training effects. We hope that the clear definitions of the spatial dimensions will stimulate further research comparing across categories. Such research would allow for better assessment of whether training one type of spatial task leads to improvements in performance on other types of spatial tasks. Finally, this well-defined framework could be used to investigate which types of spatial training would lead directly to improved performance in STEM-related disciplines.

Moderator Analyses

Despite the large number of studies that have found positive effects of training on spatial performance, other studies have found minimal or even negative effects of interventions (e.g., Faubion, Cleveland, & Harrel, 1942; Gagnon, 1985; J. E. Johnson, 1991; Kass, Ahlers, & Dugger, 1998; Kirby & Boulter, 1999; K. L. Larson, 1996; McGillicuddy-De Lisi, De Lisi, & Youniss, 1978; Simmons, 1998; J. P. Smith, 1998; Vasta, Knott, & Gaze, 1996). We analyzed the influence of several moderators, and taken together, these analyses shed substantial light on possible causes of variations in the influences of training. Considering the effects of these moderators makes the literature on spatial training substantially clearer and more tractable.

Study design and control group improvement. An important finding from this meta-analysis was the large and variable improvement in control groups. In nearly all cases, the size of the training-related improvements depended heavily on whether a control group was used and on the magnitude of gains observed within the control groups. A study that compared a trained group to a control group that improved a great deal (e.g., Sims & Mayer, 2002) may have concluded that training provided no benefit to spatial ability, whereas a study that compared its training to an less active control group (e.g., De Lisi & Wolford, 2002) may have shown beneficial effects of training. Thus, we conclude that the mixed results of past research on training can be attributed, in part, to variations in the types of control groups that were used and to the differences in performance observed among these groups.

What accounts for the magnitude of and variability in the improvement of control groups? Typically, control groups are included to account for improvement that might be expected in the absence of training. Improvement in the control groups, therefore, is seen as a measure of the effects of repeated practice in taking the assessments independent of the training intervention. Such practice effects can result from a variety of factors, including familiarity with the mode of testing (e.g., learning to press the appropriate keys in a reaction time task), improved allocation of cognitive skills such as attention and working memory, or learning of relevant test-taking strategies (e.g., gaining a sense of which kinds of foils are likely to be wrong).

In this case, however, we suggest that the improvement in the control groups may not be attributable solely to improvements that are associated with learning about individual tests. The average level of control group improvement in this meta-analysis, 0.45, was substantially larger than the average test–retest effect in other psychometric measures of 0.29 (Hausknecht et al., 2007). It is difficult to explain why this should be the case unless control groups were learning more than how to take particular tests. The spatial skills of participants in the control groups may have improved because taking spatial tests, especially multiple spatial tests, can itself be a form of training. For example, the act of taking more than one test could allow items across tests to be compared and, potentially, highlight the similarities and differences in item content (Gentner & Markman, 1994, 1997). This could, in turn, suggest new strategies or approaches for solving subsequent tasks and related spatial problems. Additionally, the spatial content used in some control groups led to greater improvement in those control groups. The finding that the overall mean weighted effect size generated from comparisons to spatial filler control groups was significantly smaller than the overall mean weighted effect size generated from comparisons to nonspatial filler control groups is consistent with the claim that spatial learning occurred in the control groups. In summary, although more work is needed to investigate these claims directly, our results call for a broader conception of what constitutes training. A full characterization of spatial training entails not only examining the content of courses or training regimens but also examining the nature of the practice effect that can result from being enrolled in a training study and being tested multiple times on multiple measures.

Age. We did not find a significant effect of age on level of improvement. This is rather surprising considering the large differential in means when comparing young children to adolescents and adults (a 0.17 difference in both cases). The vast majority of comparisons between ages came from separate studies not necessarily testing the same measures and almost certainly running their participants through different protocols. This large heterogeneity in the developmental literature, represented by the estimate of variance τ^2, generates a large standard error for the individual age groups, especially children. The large standard error in turn reduces the likelihood of finding a significant result when comparing age effects. Thus, our analyses highlight the need for further research involving systematic within-study comparisons of individuals of different ages. Although our analyses clearly suggest that spatial skills are malleable across the life span, such designs

would provide a more rigorous test of whether spatial skills are more malleable during certain periods.

Type of training. We did not find that one type of training was superior to any other. This finding may be analogous to the age effect, in that no studies in this meta-analysis compared distinct methods of training, potentially adding to the heterogeneity of the effects. However, we did find that all the methods of training studied here improved spatial skills and that all these effects differed significantly from 0, implying that spatial skills can be improved in a variety of ways. Therefore, although the research to determine which method is best is yet to be done, we can say that there is no wrong way to teach spatial skills.

Differences in the Response to Training

Sex. Both men and women responded substantially to training; however, the gender gap in spatial skills did not shrink due to training. Of course, our results do not mean that it is impossible to close the gender gap with additional training. Some studies that have used extensive training have indeed found that the gender gap can be attenuated and perhaps eliminated (e.g., Feng et al., 2007). In addition, many training studies have shown that individual differences in initial level of performance moderate the trajectory of improvements with training (Just & Carpenter, 1985; Terlecki et al., 2008). For example, Terlecki et al. (2008) showed that female participants who initially scored poorly improved slowly at first but improved more later in training. In contrast, males and females with initially higher scores improved the most early in training. This study did not include low-scoring males. This difference in learning trajectory is important because it suggests that if training periods are not sufficiently long, female participants will appear to benefit less from training and show smaller training-related gains than male participants. Additionally, Baenninger and Newcombe (1989) pointed out that improvement among females will likely not close the gender gap until improvement among males has reached asymptote, which is difficult to determine. Therefore, whether the gender gap *can* be closed, with appropriate methods of training, still remains very much an open question, but what is clear is that both men and women can improve their spatial skills significantly with training.

More generally, efforts that focus on closing the gender gap of specific spatial skills, such as mental rotation, may be misplaced. Differences in performance on isolated spatial skills are of interest for theoretical reasons. However, the recent increases in emphasis on decreasing the gender gap in measures of STEM success (i.e., grades and achievement in STEM disciplines) suggest that training individual spatial skills is desirable only if the training translates into success in STEM. It may be possible that STEM success can be achieved without eliminating the gender gap on basic spatial measures. For example, one possible view is that being able to work in STEM fields is dependent on achieving a threshold level of performance rather than being dependent on achieving absolute parity in performance between males and females. Note that this threshold would be a lower limit, below which individuals are not likely to enter a STEM field. Our use of the term *threshold* contrasts with that of Robertson, Smeets, Lubinski, and Benbow (2010), who have argued that there is no upper threshold for the relation between various cognitive abilities and STEM achievement and attainment at the highest levels of eminence. The goal of future research perhaps should not be to focus on remediation in order to close the gender gap in basic spatial skills but rather to close the gap in STEM interest and entry into STEM-based occupations.

Initial level of performance. Finally, we found that initial level of spatial skills affected the degree of malleability. Participants who started at lower levels of performance improved more in response to training than those who started at higher levels. In part, this effect could stem from a ceiling that limits the improvement of participants who begin at high levels. However, in some studies (e.g., Terlecki et al., 2008), scores were not depressed by ceiling effects, so it is possible that we are seeing the beginnings of asymptotic performance. Nevertheless, it is important to note that improvement was not limited only to those who began at particularly low levels.

Contributions of the Novel Meta-Analytic Approach

The approach developed by Hedges et al. (2010a, 2010b) helps to control for the fact that most studies in this meta-analysis report results from multiple experiments. Importantly, this method does not require any effect sizes to be disregarded, while correctly taking into account the levels of nesting. The estimation method provided by this approach is robust in many important ways; for example, unlike most estimation routines for hierarchical meta-analyses, it is robust to any misspecification of the weights and does not require the effect sizes to be normally distributed.

By taking nesting into account, the calculations appreciate that there are multiple types of variance across the literature. In addition to taking into account sampling variability, the approach by Hedges et al. (2010a, 2010b) estimates the variance between effect sizes from experiments within a single study, ω^2, and the variance between average effect sizes in different studies, τ^2. By using all three factors to calculate the standard error for a mean weighted effect size, this methodology reflects the heterogeneity in the literature. That is, the larger the heterogeneity, the larger the standard error produced, and the less likely comparison groups will be found to be statistically significantly different. It is the combination of this weighting and the robust estimation routine that allows us to be very confident in the significant differences found within our data set. Two examples from our analyses illustrate well the importance of taking these parameters into account; we found no significant effect of age and no significant differences between the types of training, but the lack of differences may stem in part from the fact that studies tend to include only one age group (occasionally two groups) and to include only one type of training.

Mechanisms of Learning and Improvement

The evidence suggests that a wide range of training interventions improve spatial skills. The findings of the present analysis suggest that comparing and attempting to optimize different methods of training may serve as an important focus for future research. This process of optimizing training should be informed by our empirical and theoretical knowledge of the mechanisms through which training leads to improvements. Considering the basic cognitive processes, such as attention and memory, required to perform spatial tasks, may inform our efforts to understand how

individuals improve on these processes and facilitate relevant training.

Mental rotation is one example of a domain in which the mechanisms of improvement are reasonably well understood. Part of the mechanism is simply that participants become faster at rotating the objects in their minds (Kail & Park, 1992). This source of improvement is reflected in the slope of the line that relates response time to the angular disparity between the target and test figures, but other aspects of performance improve as well. The *y*-intercept of the line that relates response time to angular disparity also decreases (Heil et al., 1998; Terlecki et al., 2008) and may change more consistently then the slope of this line (Wright et al., 2008). Researchers initially assumed that changes in the *y*-intercept reflected basic changes in reaction time (e.g., shortened motor response to press the computer key) as opposed to substantive learning. However, recent work suggests that these changes actually may be meaningful and important. For example, Wright et al. (2008) argued that intercept changes following training may reflect improved encoding of the stimuli. They suggested that training interventions need not focus exclusively on training the mental transformation process, which targets the slope, but should also focus on facilitating initial encoding, since this should also improve mental rotation performance (Amorim, Isableu, & Jarraya, 2006). Individual differences also moderate the impact of training on mental rotation (e.g., Terlecki et al., 2008). For example, Just and Carpenter (1985) found that as training progressed, individuals who were high in spatial ability were more adept and flexible at performing rotations of items about nonprincipal axes, suggesting that they were able to adapt to the variety of coordinate systems represented by the test items.

Training-related improvements in mental rotation and other spatial tasks also likely occur through some basic cognitive pathways, such as improved attention and memory. Spatial skills are obviously affected by the amount of information that can be held simultaneously in memory. Many spatial tasks require holding in working memory the locations of different objects, landmarks, etc. Research indicates that individual differences in (spatial) working memory capacity are responsible for some of the observed differences in performance on spatial tasks. As Hegarty and Waller (2005) suggested, individuals who cannot hold information in working memory may "lose" the information that they are trying to transform. Several lines of research indicate that spatial attentional capacity improves with relevant training (e.g., Castel, Pratt, & Drummond, 2005; Feng et al., 2007; Green & Bavelier, 2007). Instructions or training that improves working memory and attentional capacities is therefore likely to enhance the amount of information that participants can think about and act on.

A good example of interventions that improve working memory capacity comes from research on the effect of video game playing on performance on a host of spatial attention tasks. Video game players performed substantially better in several tasks that tap spatial working memory, such as a subitization–enumeration task that requires participants to estimate the number of dots shown on a screen in a brief presentation. Most people can recognize (subitize) five or fewer dots without counting; after this point, performance begins to decline in typical nonvideo game players and counting is required. However, video game players can subitize a larger number of dots—approximately seven or eight (e.g., Green & Bevalier, 2003, 2007). Thus, the additional subitization capacity suggests that video game players can hold a greater number of elements in working memory and act upon them. Likewise, video game players appear to have a smaller attentional blink, allowing them to take in and use more information across the range of spatial attention. In addition, many spatial tasks and transformations can be accomplished by the application of rules and strategies. For example, Just and Carpenter (1985) found that many participants completed mental rotations not by rotating the entire stimulus mentally but by comparing specific aspects of the figure and checking to determine whether the corresponding elements would match after rotation. Likewise, advancement in the well-known spatial game Tetris is often accomplished by the acquisition of specific rules and strategies that help the participant learn when and how to fit new pieces into existing configurations. Furthermore, spatial transformations in chemistry (Stieff, 2007) are often accomplished by learning and applying specific rules that specify the spatial properties of molecules. In summary, part of learning and development (and hence one of the effects of training) may be the acquisition and appropriate application of strategies or rules.

Educational and Policy Implications

The present meta-analysis has important implications for policy decisions. It suggests that spatial skills are moderately malleable and that a wide variety of training procedures can lead to meaningful and durable improvements in spatial ability. Although our analysis appears to indicate that certain recreational activities, such as video games, are comparable to formal courses in the extent to which they can improve spatial skills, we cannot assume that all students will engage in this type of spatial skills training in their spare time. Our analysis of the impact of initial performance on the effect of training suggests that those students with initially poor spatial skills are most likely to benefit from spatial training. In summary, our results argue for the implementation of formal programs targeting spatial skills.

Prior research gives us a way to estimate the consequences of administering spatial training on a large scale in terms of producing STEM outcomes. Wai, Lubinski, Benbow, and Steiger (2010) have established that STEM professionals often have superior spatial skills, even after holding constant correlated abilities such as math and verbal skills. Using a nationally representative sample, Wai et al. (2009) found that the spatial skills of individuals who obtained at least a bachelor's degree in engineering were 1.58 standard deviations greater than the general population (D. Lubinski, personal communication, August 14, 2011; J. Wai, personal communication, August 17, 2011). The very high level of spatial skills that seems to be required for success in engineering (and other STEM fields) is one important factor that limits the number of Americans who are able to become engineers (Wai et al., 2009, 2010) and thus contributes to the severe shortage of STEM workers in the United States.

In this article, we have demonstrated that spatial skills can be improved. To put this finding in context, we asked how much difference this improvement would make in the number of students whose spatial skills meet or exceed the average level of engineers' spatial skills. We calculated the expected percentage of individuals who would have a Z score of 1.58 before and after training. To provide the most conservative estimate, we used the effect of spatial training that was derived from the most rigorous studies, the

mixed design, which included control groups and measured spatial skills both before and after training. The mean effect size for these studies was 0.40. As shown in Figure 6, increasing the population level of spatial skills by 0.40 standard deviation would approximately double the number of people who would have levels of spatial abilities equal to or greater than that of current engineers.

We recognize that our estimate entails many assumptions. Perhaps most importantly, our estimate of the impact of increased spatial training implies a causal relationship between spatial training and improvement in STEM learning or attainment. Unfortunately, this assumption has rarely been tested, and has, to our knowledge, never been tested with a rigorous experimental design, such as randomized control trials. Thus, the time is ripe to conduct full, prospective, and randomized tests of whether and how spatial training can enhance STEM learning.

An example of when and how spatial training might benefit STEM learning. There are many ways in which spatial training may facilitate STEM attainment, achievement, and learning. Comprehensive discussions on these STEM topics have been offered elsewhere (e.g., Newcombe, 2010; Sorby & Baartmans, 1996). Here we concentrate on one example that we believe highlights particularly well the potential of spatial training to improve STEM achievement and attainment.

Although it certainly may be useful to ground early STEM learning in spatially rich approaches, our results suggest that it may be possible to help students even after they have finished high school. Specifically, we suggest that spatial training might increase the retention of students who have expressed interest in and perhaps already begun to study STEM topics in college. One of the most frustrating challenges of STEM education is the high dropout rate among STEM majors. For example, in Ohio public universities, more than 40% of the students who declare a STEM major leave the STEM field before graduation (Price, 2010). The relatively high attrition rates among self-identified STEM students are

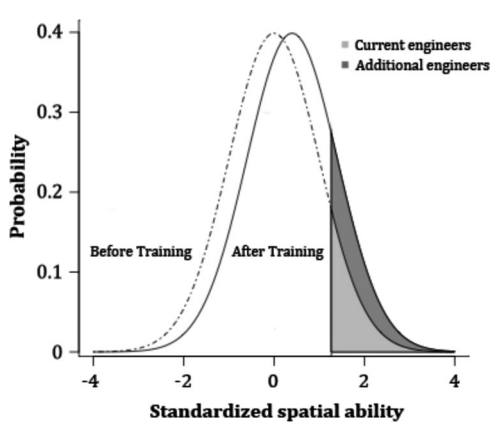

Figure 6. Possible consequences of implementing spatial training on the percentage of individuals who would have the spatial skills associated with receiving a bachelor's degree in engineering. The dotted line represents the distribution of spatial skills in the population before training; the solid line represents the distribution after training. Shifting the distribution by .40 (the most conservative estimate of effect size in this meta-analysis) would approximately double the amount of people who have the level of spatial skills associated with receiving a bachelor's degree in engineering. Data based on Wai et al. (2009, 2010).

particularly disappointing because these students are the "low hanging fruit" in terms of increasing the number of STEM workers in the United States. They have already attained the necessary prerequisites to pursue a STEM field at the college level, yet even many of these highly qualified students do not complete a STEM degree. Thus, an intervention that could help prevent early dropout among STEM majors might prove to be particularly helpful.

We suggest that spatial training might help lower the dropout rate among STEM majors. The basis for this claim comes from analyses (e.g., Hambrick et al., 2011; Hambrick & Meinz, 2011; Uttal & Cohen, in press) of the trajectory of importance for spatial skills in STEM learning. Psychometrically assessed spatial skills strongly predict performance early in STEM learning. However, psychometrically assessed spatial skills actually become less important as students progress through their STEM coursework and move toward specialization. For example, Hambrick et al. (2011) showed that psychometric tests of spatial skills predicted performance among novice geologists but did not predict performance in an expert-level geology mapping task among experts. Likewise, psychometrically assessed spatial skills predicted initial performance in physics coursework but became less important after learning was complete (Kozhevnikov, Motes, & Hegarty, 2007). Experts can rely on a great deal of semantic knowledge of the relevant spatial structures and thus can make judgments without having to perform classic mental spatial tasks such as rotation or two- to three-dimensional visualization. For example, experts know about many geological sites and might know the underlying structure simply from learning about it in class or via direct experience. At a more abstract level, geology experts might be able to solve spatial problems by analogy, thinking about how the structure of other well-known outcrops might be similar or different from the one they are currently analyzing. Similarly, expert chemists often do not need to rely on mental rotation to reason about the spatial properties of two molecules because they may know, semantically, that the target and stimulus are chiral (i.e., mirror images) and hence can respond immediately without having to rotate the stimulus mentally to match the target. This decision could be made quickly, regardless of the degree of angular disparity, because the chemist knows the answer as a semantic fact, and hence mental rotation is not required.

Such findings and theoretical analyses led Uttal and Cohen (in press) to propose what that they termed the Catch-22 of spatial skills in early STEM learning. Students who are interested in STEM but have relatively low levels of spatial skills may face a frustrating challenge: They may have difficulty performing the mental operations that are needed to understand chemical molecules, geological structures, engineering designs, etc. Moreover, they may have difficulty understanding and using the many spatially rich paper- or computer-based representations that are used to communicate this information (see C. A. Cohen & Hegarty, 2007; Stieff, 2007; Uttal & Cohen, in press). If these students could just get through the early phases of learning that appear to be particularly dependent on decontextualized spatial skills, then their lack of spatial skills might become less important as semantic knowledge increased. Unfortunately, their lack of spatial skills keeps them from getting through the early classes, and many drop out. Thus, spatial skills may act as a gatekeeper for students interested in STEM; those with low spatial skills may have par-

ticular problems getting through the very challenging introductory-level classes.

Spatial training of the form reviewed in this article could be particularly helpful for STEM students with low spatial skills. Even a modest increase in the ability to rotate figures, for example, could help some students solve more organic chemistry problems and thus be less likely to drop out. In fact, some research (e.g., Sorby, 2009; Sorby & Baartmans, 2000) does suggest that spatial training focusing on engineering students who self-identify as having problems with spatial tasks can be particularly helpful, resulting in both very large gains in psychometrically assessed spatial skills and lower dropout rates in early engineering classes that appear to depend heavily on spatial abilities.

Of course, spatial training at earlier ages might be even more helpful. For example, Cheng and Mix (2011; see also Mix & Cheng, 2012) recently demonstrated that practicing spatial skills improved math performance among first and second graders. Results indicate that spatial training is effective at a variety of skill levels and ages; further research is needed to determine how effective this training will be in improving STEM learning.

Selecting an intervention. There is not a single answer to the question of what works best or what we should do to improve spatial skills. Perhaps the most important finding from this meta-analysis is that several different forms of training can be highly successful. Decisions about what types of training to use depend on one's goals as well as the amount of time and other resources that can be devoted to training. Here we give two examples of training that has worked well and that may not require substantial resources.

One example of a highly effective but easy to administer form of training comes from the work of McAuliffe, Piburn, Reynolds, and colleagues. They have demonstrated that adding spatially challenging activities to standard courses (e.g., high school physics) can further improve spatial skills. For example, in one study (McAuliffe, 2003), 2 days of training students in a physics class to use two- and three-dimensional representations consistently led to improvement and transfer to a spatially demanding task, reading a topographical map. Improvement was compared to students performing normal course work. This treatment did not require extensive intervention or the use of expensive materials, and it was incorporated into standard classes. It was administered in two consecutive class periods on different days, and the posttest was a visualizing topography test administered the day following the completion of the training. McAuliffe (2003) found an overall effect size of 0.64. Therefore, with relatively simple interventions, implemented in a traditional high school course, participants improve on spatially challenging posttests.

The positive returns gained from classroom instruction should not limit the teaching tools available for spatial ability. For example, there is great excitement about the possibility of using video games in both formal and informal education (e.g., Federation of American Scientists, 2006; Foreman et al., 2004; Gee, 2003). Our results highlight the relevance of video games for improving spatial skills. For example, Feng et al. (2007) investigated the effects of video game playing on spatial skills, including transfer to mental rotation tasks. They focused on action (Medal of Honor; single-user role playing) versus nonaction (Ballance; 3-D puzzle solving) video games. A total of 10 hr of training was administered over 4 weeks. Participants who played the action game performed much better than those who played the control game. The average effect size was 1.19. This result indicates that playing active games has the potential to enhance spatial thinking substantially, even when compared to a strong control group. These activities can be done outside school and hence do not need to displace in-school activities. The policy question here is how to encourage this kind of game playing.

The above examples address the training needs of adolescents and adults. Although elementary school children also play video games, there are likely different ways to enhance the spatial ability of very young children, including block play, puzzle play, the use of spatial language by parents and teachers, and the use of gesture. For an overview of spatial interventions for younger children, see Newcombe (2010).

Conclusion

Most efforts aimed at educational reform focus on reading or science. This focus is appropriate because achievement in these areas is readily measured and of great interest to educators and policy makers. However, one potentially negative consequence of this focus is that it misses the opportunity to train basic skills, such as spatial thinking, that can underlie performance in multiple domains. Recent research is beginning to remedy this deficit, with an increase in work examining the link between spatial thinking and performance in STEM disciplines such as biology (Lennon, 2000), chemistry (Coleman & Gotch, 1998; Wu & Shah, 2004), and physics (Kozhevnikov et al., 2007); as well as the relation of spatial thinking to skills relevant to STEM performance in general (Gilbert, 2005), such as reasoning about scientific diagrams (Stieff, 2007). Our hope is that our findings on how to train spatial skills will inform future work of this type and, ultimately, lead to highly effective ways to improve STEM performance.

For many years, much of the focus of research on spatial cognition and its development has been on the biological underpinnings of these skills (e.g., Eals & Silverman, 1994; Kimura, 1992, 1996; McGillicuddy-De Lisi & De Lisi, 2001; Silverman & Eals, 1992). Perhaps as a result, relatively little research has focused on the environmental factors that influence spatial thinking and its improvement. Our results clearly indicate that spatial skills are malleable. Even a small amount of training can improve spatial reasoning in both males and females, and children and adults. Spatial training programs therefore may play a particularly important role in the education and enhancement of spatial skills and mathematics and science more generally.

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(*Appendices follow*)

Appendix A

Coding Scheme Used to Classify Studies Included in the Meta-Analysis

Publication Status

Articles from peer-reviewed journals were considered to be published, as were research articles in book chapters. Articles presented at conferences, agency and technical reports, and dissertations were all considered to be unpublished work. If we found both the dissertation and the published version of an article, we counted the study only once as a published article. If any portion of a dissertation appeared in press, the work was considered published.

Study Design

The experimental design was coded into one of three mutually exclusive categories: *within subject*, defined as a pretest/posttest for only one subject group; *between subject*, defined as a posttest only for a control and treatment group; and *mixed* design, defined as a pretest/posttest for both control and treatment groups.

Control Group Design and Details

For each control group, we noted whether a single test or a battery of tests was administered. We also noted the frequency with which participants received the tests (i.e., repeated practice or pretest/posttest only). Finally, if the control group was administered a filler task, we determined if it was spatial in nature.

Type of Training

We separated the studies into three training categories:

Video game training. In these studies, the training involved playing a video or computer game (e.g., Zaxxon, in which players navigate a fighter jet through a fortress while shooting at enemy planes). Because many types of spatial training use computerized tasks that share some similarities with video games, we defined a video game as one designed primarily with an entertainment goal in mind rather than one designed specifically for educational purposes. For example, we did not include interventions that involved learning the programming language Logo because they are not typically presented as games.

Course training. These studies tested the effect of being enrolled in a course that was presumed to have an impact on spatial skills. Inclusion in the course category indicated that either the enrollment in a semester-long course was the training manipulation (e.g., engineering graphics course) or the participant took part in a course that required substantial spatial thinking (e.g., chess lessons, geology).

Spatial task training. Spatial training was defined as studies that used practice, strategic instruction, or computerized lessons. Spatial training was often administered in a psychology laboratory.

Typology: Spatial Skill Trained and Tested (See Method and Table 1)

Sex. Whenever possible, effect sizes were calculated separately for males and females, but many authors did not report differences broken down by sex. In cases where separate means were not provided for each sex, we contacted authors for the missing information and received responses in eight cases. If we did not receive a reply from the authors, or the author reported that the information was not available, we coded sex as not specified.

Age. The age of the participants used was identified and categorized as either children (under 13 years old), adolescent (13–18 years inclusive), or adult (over 18 years old).

Screening of Participants

Because some intervention studies focus on the remediation of individuals who score relatively poorly on pretests, we used separate codes to distinguish studies in which low-scoring individuals were trained exclusively and those in which individuals received training regardless of pretest performance.

Durability

We noted how much time elapsed from the end of training to the administration of the posttest. We incorporated data from any follow-ups that were conducted with participants to assess the retention and durability of training effects.

(*Appendices continue*)

Appendix B

Method for the Calculation of Effect Sizes (Hedges's *g*) by Comprehensive Meta-Analysis

To calculate Hedges's *g* when provided with the means and standard deviations for the pretest and posttest of the treatment and control groups, the standardized mean difference (*d*) is multiplied by the correction factor (*J*).

Example raw data: treatment (T): pretest = 7.87, *SD* = 4.19, posttest = 16.0, *SD* = 4.07, *N* = 8; control (C): pretest = 5.22, *SD* = 3.96, posttest = 8.0, *SD* = 5.45, *N* = 9; pre- or posttest correlation = .7.

Calculation of the standardized mean difference (*d*):

$$d = \frac{\text{Raw Diffrence Between the Means}}{SD \text{ Change Pooled}}$$

Raw Difference Between the Means = Mean Change T − Mean Change C

$$\text{Mean Change T} = \text{Mean Post T} - \text{Mean Pre T} = 16.0 - 7.87 = 8.13$$

$$\text{Mean Change C} = \text{Mean Post C} - \text{Mean Pre C} = 8.0 - 5.22 = 2.78$$

$$\text{Raw Difference Between the Means} = 8.13 - 2.78 = \mathbf{5.35}$$

SD Change Pooled

$$= \sqrt{\frac{(N_T - 1)(SD \text{ Change } T)^2 + (N_C - 1)(SD \text{ Change } C)^2}{(N_T + N_C - 2)}}$$

SD Change Pooled

$$= \sqrt{[(SD \text{ Pre T})^2 + (SD \text{ Post T})^2 - 2(\text{Pre Post Corr})(SD \text{ Pre T})(SD \text{ Post T})]}$$

$$= \sqrt{[(4.19)^2 + (4.07)^2 - 2(0.7)(4.19)(4.07)]}$$

$$= 3.20$$

SD Change C

$$= \sqrt{[(SD \text{ Pre C})^2 + (SD \text{ Post C})^2 - 2(\text{Pre Post Corr})(SD \text{ Pre C})(SD \text{ Post C})]}$$

$$= \sqrt{[(3.96)^2 + (5.45)^2 - 2(0.7)(3.96)(5.45)]}$$

$$= 3.89$$

$$SD \text{ Change Pooled} = \sqrt{\frac{(8 - 1)(3.20)^2 + (9 - 1)(3.89)^2}{(8 + 9 - 2)}} = \mathbf{3.58}$$

$$d = \frac{5.35}{3.58} = \mathbf{1.49}$$

$$SE\ d = \sqrt{\frac{1}{N_T} + \frac{1}{N_C} + \frac{d^2}{2(N_T + N_C)}} = \sqrt{\frac{1}{8} + \frac{1}{9} + \frac{1.49^2}{2(8 + 9)}} = 0.55$$

Calculation of the correction factor (*J*):

$$J = 1 - \frac{3}{4*df - 1}$$

$$df = (N_{total} - 2) = (8 + 9 - 2) = 15$$

$$= 1 - \frac{3}{4*15 - 1} = 0.95$$

Calculation of Hedges's *g*:

$$g = d * J = 1.49 * 0.95 = \mathbf{1.42}$$

$$SE\ g = SE\ d * J = 0.55 * 0.95 = 0.52$$

$$\text{Variance of } g = SE\ g^2 = 0.52^2 = 0.27$$

Hedges's *g* was also calculated if the data were reported as an *F* value for the difference in change between treatment and control groups. The equations are provided here:

$$\text{Standard Change Difference} = \sqrt{\frac{N_T + N_C}{N_T * N_C}}$$

Standard Change Difference *SE*

$$= \sqrt{\frac{1}{N_T} + \frac{1}{N_C} + \frac{\text{Standard Change Difference}^2}{2 * N_T + N_C}}$$

(*Appendices continue*)

The calculations for the correction factor (J) and Hedges's g are the same as above.

Hedges's g was also calculated if the data were reported as a t value for the difference between the treatment and control groups. The equations are provided here:

$$\text{Standard Paired Difference} = \frac{t}{\sqrt{N}}$$

$$\text{Standard Paired Difference } SE = \frac{t}{\sqrt{N}} * \sqrt{\frac{1 + \text{Standard Paired Difference}^2}{2}}$$

The calculations for the correction factor (J) and Hedges's g are the same as above. Standard Paired Difference replaces d and Standard Paired Difference SE replaces SE d.

Appendix C

Mean Weighted Effect Sizes and Key Characteristics of Studies Included in the Meta-Analysis

Study	g	k	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Alderton (1989)	0.383	16	Repeated practice on the test used for pre- and posttest	3	Integrating Details task, mental rotations tests, Intercept tasks	1, 2	1, 2	2
Alington et al. (1992)	0.517	6	Repeated practice on mental rotation tasks	3	V–K MRT	2	1, 2	3
Asoodeh (1993)	0.765	5	Animated graphics used to present orthographic projection treatment module	3	Orthographic projection quiz, V–K MRT	2	3	3
Azzaro (1987): Overall	0.297	6	Recreation activities with emphasis on spatial orientation	3	STAMAT–Object Rotation	2	1	4
Azzaro (1987): Control	0.251	4						
Azzaro (1987): Treatment	0.412	2						
Baldwin (1984): Overall	0.704	2	Ten lessons in spatial orientation and spatial visualization tasks	3	GEFT and DAT combined score	1, 2	1, 2	1
Baldwin (1984): Control	0.393	2						
Baldwin (1984): Treatment	0.832	2						
Barsky & Lachman (1986): Overall	0.288	10	Physical knowledge versus reference system versus control (observe and think only)	3	RFT, WLT, Plumb-Line task, EFT, PMA–SR	1, 2, 3	1	3
Barsky & Lachman (1986): Control	−0.018	4						
Barsky & Lachman (1986): Treatment	0.372	8						
Bartenstein (1985)	0.185	4	Visual skills training program: 8 hr of drawing activities	3	Monash Spatial test, Space Thinking (Flags), CAPS–SR, Closure Flexibility	1, 2	3	3
Basak et al. (2008): Overall	0.566	2	Quick battle solo mission in Rise of Nations video game	1	Battery of mental rotation cognitive assessment from Rise of Nations	2	3	3
Basak et al. (2008): Control	0.256	2						
Basak et al. (2008): Treatment	0.564	1						
Basham (2006)	0.308	6	Professional desktop CADD solid modeling software	3	PSVT	2	3	2

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Batey (1986)	0.502	16	Highly specific training versus nonspecific training (instruction in orthographic projection) versus control (no training)	3	SR–DAT, Horizontality test, V–K MRT, GEFT	1, 2, 3	1, 2	2
Beikmohamadi (2006)	0.181	12	Web-based tutorial on valence shell electron repulsion theory and molecular visualization skills	3	PSVT, Shape Identification test	1, 2	3	3
Ben-Chaim et al. (1988)	1.08	14	Fifth-, sixth, seventh, and eighth graders from inner-city, rural, and suburban schools trained in spatial visualization (concrete activities, building, drawing solids)	3	Middle Grades Mathematics Project Spatial Visualization test	2	1, 2	1
Blatnick (1986): Overall	−0.080	2	Verbal instruction, demo, and assembly of molecular molecules	3	General Aptitude Test Battery– Spatial	2	1, 2	2
Blatnick (1986): Control	0.500	2						
Blatnick (1986): Treatment	0.333	2						
Boakes (2006): Overall	0.277	6	Origami lessons	3	Paper Folding task, Surface Development test, Card Rotation test	2	1, 2	1
Boakes (2006): Control	0.446	6						
Boakes (2006): Treatment	0.378	6						
Boulter (1992)	0.384	3	Transformational Geometry with Object Manipulation and Imagery	2	Surface Development test, Card Rotations test, Hidden Patterns test	1, 2	3	2
Braukmann (1991): Overall	0.301	3	Along with lecture on orthographic projection, 3-D CAD versus control (traditional 2-D manual drafting) training	3	Test of Orthographic Projection Skills, Shepard and Metzler cube test	2	3	3
Braukmann (1991): Control	0.664	2						
Braukmann (1991): Treatment	0.430	3						
Brooks (1992): Overall	0.540	6	Interaction strategy of explaining disagreement	3	Structural Index Score: Placing a house in spatial relations scene	4	1, 2, 3	1
Brooks (1992): Control	0.182	6						
Brooks (1992): Treatment	0.585	6						
Calero & Garcia (1995)	0.600	4	Instrumental enrichment program to improve subject's orientation of own body	3	Practical Spatial Orientation, Thurstone's spatial ability test from PMA	2, 4	3	3
Cathcart (1990): Overall	0.428	1	Course training in Logo	2	GEFT	1	3	1
Cathcart (1990): Control	0.527	1						
Cathcart (1990): Treatment	0.941	1						
Center (2004): Overall	0.296	1	Building Perspective Deluxe software	3	V–K MRT	2	3	1
Center (2004): Control	0.455	1						
Center (2004): Treatment	0.312	1						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Chatters (1984)	0.559	2	Groups comparable in visual–motor perceptual skill given video game training (Space Invaders) versus control (no training)	1	Block Design, Mazes (both WISC subtests)	1, 2	3	1
Cherney (2008): Overall	0.352	12	Antz Extreme Racing in 3-D space with joystick	1	V–K MRT	2	1, 2	3
Cherney (2008): Control	0.471	8						
Cherney (2008): Treatment	0.645	4						
Chevrette (1987)	−0.078	2	Computer simulation game asking subjects to locate urban land uses in three cities	1	GEFT	1	3	3
Chien (1986): Overall	0.281	6	Computer graphics spatial training	3	Author created Mental Rotation test	2	1, 2	1
Chien (1986): Control	0.320	6						
Chien (1986): Treatment	0.479	6						
Clark (1996)	−0.646	2	Computer graphics designed to aide spatial perception	3	Restaurant Spatial Comparison test	1	1, 2	3
Clements et al. (1997)	1.226	2	Geometry training in slides, flips, turns, etc., using video game Tumbling Tetronimoes	1	Wheatley Spatial test (MRT)	2	1, 2	1
Cockburn (1995): Overall	0.649	6	Play with LEGO Duplo blocks and build objects	3	Kinesthetic Spatial Concrete Building test, Kinesthetic Spatial Concrete Matching test, Motor Free Visual Perception test	1, 2	1	1
Cockburn (1995): Control	0.456	6						
Cockburn (1995): Treatment	0.895	6						
Comet (1986): Overall	0.541	1	Art to improve realistic drawing skills	3	EFT	1	3	3
Comet (1986): Control	0.269	1						
Comet (1986): Treatment	0.104	1						
Connolly (2007): Overall	0.085	4	Practice converting 2-D to 3-D, 3-D to 2-D, and Boolean operations to combine objects spatially	3	Paper Folding task, Spatial Orientation Cognitive Factor test	2	3	3
Connolly (2007): Control	0.550	4						
Connolly (2007): Treatment	0.546	4						
Crews (2008)	−0.103	2	Teacher participation in Geospatial Technologies professional development	2	Spatial Literacy Skills	2	1, 2	2
Curtis (1992)	0.191	3	Orthographic principles with glass box and bowl/hemisphere imagery	3	Multiview orthographic projection	2	3	3
Dahl (1984)	−0.157	3	Computer-aided orthographic training–projection problems	2	Multiple Aptitudes Test 8/9: Choose the correct piece to finish the figure, GEFT	1, 2	3	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
D'Amico (2006): Overall	2.118	1	Verbal and visuospatial working memory	3	Visuospatial Working Memory test	2	3	1
D'Amico (2006): Control	−0.773	1						
D'Amico (2006): Treatment	0.820	1						
Day et al. (1997)	1.420	2	Block design training	3	Block Design (WPPSI subtest)	2	3	1
Del Grande (1986)	0.984	1	Geometry intervention	3	Author designed tests that span across outcome categories	5	3	1
De Lisi & Cammarano (1996): Overall	0.689	2	Video game training with Blockout versus control (Solitaire)	1	V–K MRT	2	1, 2	3
De Lisi & Cammarano (1996): Control	0.227	2						
De Lisi & Cammarano (1996): Treatment	0.573	2						
De Lisi & Wolford (2002): Overall	1.341	2	Video game training with Tetris versus control (Carmen Sandiego)	1	French Kit Card Rotation test	2	1, 2	1
De Lisi & Wolford (2002): Control	−0.058	2						
De Lisi & Wolford (2002): Treatment	0.591	2						
Deratzou (2006)	0.583	10	Visualization training with problems sets, journals, videos, lab experiments, computers	2	Card Rotation test, Cube Comparison test, Form Board test, Paper folding task, Surface Development test	2	1, 2	2
Dixon (1995)	0.543	4	Geometer's Sketchpad spatial skills training	3	Paper folding task, Card Rotation test, Computer and Paper–Pencil Rotation/Reflection instrument	2	3	2
Dorval & Pepin (1986): Overall	0.354	2	Zaxxon video game playing versus control (no game play)	1	EFT	1	1, 2	3
Dorval & Pepin (1986): Control	0.260	2						
Dorval & Pepin (1986): Treatment	0.549	2						
Duesbury (1992)	1.520	12	Orthographic techniques, line and feature matching, instruction and practice visualizing	3	Surface Development test, Flanagan Industrial test, Paper Folding task, test of 3-D shape visualization	2	2	3
Duesbury & O'Neil (1996)	0.648	4	Wireframe CAD training on orthographic projection, line–feature matching, 2- and 3-D visualization versus control (traditional blueprint reading course)	3	Flanagan Industrial Tests Assembly, SR–DAT, Surface Development test, Paper Folding task	2	2	3
Dziak (1985)	0.115	1	Instruction in BASIC graphics	3	Card Rotations test	2	3	2
Edd (2001)	0.383	1	Practice with rotating/handling MRT models	3	Shepard–Metzler MRT	2	1	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Ehrlich et al. (2006): Overall	0.620	6	Imagine and actually move pieces with instruction	3	Mental Rotations test	2	1, 2	1
Ehrlich et al. (2006): Control	1.091	4						
Ehrlich et al. (2006): Treatment	0.873	2						
Eikenberry (1988): Overall	0.311	4	Learning to program in Logo	2	Space Thinking Flags test: Mental Rotation, Children's GEFT	1, 2	1, 2	1
Eikenberry (1988): Control	0.518	4						
Eikenberry (1988): Treatment	0.514	4						
Embretson (1987)	0.686	3	Paper folding training versus control (clerical training)	3	SR–DAT	2	3	3
Engelhardt (1987)	1.190	1	Guided instruction to construct block designs from a model	3	Block Design (WPPSI), DAT Spatial Folding task, SR–DAT	2	3	1
Eraso (2007): Overall	0.282	6	Geometer's Sketchpad interactive computer program	2	PSVT	2	1, 2	2
Eraso (2007): Control	0.486	4						
Eraso (2007): Treatment	0.375	2						
Fan (1998)	0.505	12	Drawing with instructional verbal cues and visual props	3	Correct responses to selection task, representation of size relationship, hidden outlines, and occlusion in drawing	2	3	1
Feng (2006): Overall	1.137	2	Training using action versus control (nonaction video game)	1	V–K MRT	2	1, 2	3
Feng (2006): Control	0.186	2						
Feng (2006): Treatment	1.136	2						
Feng et al. (2007): Overall	1.194	4	Training using action versus control (nonaction video game)	1	V–K MRT	2	1, 2	3
Feng et al. (2007): Control	0.400	4						
Feng et al. (2007): Treatment	1.347	4						
Ferguson (2008): Overall	0.257	3	Engineering drawing with dissection of handheld and computer-generated manipulatives	3	PSVT–Rotations	2	3	3
Ferguson (2008): Control	0.197	2						
Ferguson (2008): Treatment	0.107	1						
Ferrara (1992)	−0.424	1	Imagery instruction with visual synthesis task	3	Draw shapes from training by hand and on computer	2	3	2
Ferrini-Mundy (1987): Overall	0.344	4	Audiovisual spatial visualization training, with or without tactual practice, versus Control 1 (posttest-only group)	2	SR–DAT	2	3	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Ferrini-Mundy (1987): Control	0.655	1	Audiovisual spatial visualization training, with or without tactual practice versus Control 2 (calculus course as usual)					
Ferrini-Mundy (1987): Treatment	0.620	2						
Fitzsimmons (1995): Overall	0.232	8	Solving 3-D geometric problems in calculus	2	PSVT–Rotations and visualization of views	2	3	3
Fitzsimmons (1995): Control	0.116	2						
Fitzsimmons (1995): Treatment	0.150	8						
Frank (1986): Overall	0.490	10	Map reading, memetic or itinerary	3	Posttest score in locating animal using a map, symbol recognition, representational correspondence (route items and landmark items)	2	1, 2, 3[e]	1
Frank (1986): Control	0.790	4						
Frank (1986): Treatment	0.687	4						
Funkhouser (1990)	0.420	2	Geometry course or second-year algebra plus computer problem-solving activities	2	Problem-solving test: spatial subtest	1	1, 2	1
Gagnon (1985): Overall	0.310	3	Playing 2-D Targ and 3-D Battlezone video games versus control (no video game playing)	1	Guilford–Zimmerman Spatial Orientation and Visualization; Employee Aptitude Survey: Visual Pursuit test	1, 2, 4	3	3
Gagnon (1985): Control	0.346	3						
Gagnon (1985): Treatment	0.507	3						
Gagnon (1986)	0.156	3	Video game training: Interactive versus observational	1	Guilford–Zimmerman MRT	2	1	3
Geiser et al. (2008)	0.674	2	Administered MRT test twice as practice	3	MRT described in Peters et. al (1995)	2	1, 2	1
Gerson et al. (2001): Overall	0.087	5	Engineering course with lecture and spatial modules versus control (course and modules without lecture)	2	SR–DAT, Mental Cutting test, MRT, 3-DC cube test, PSVT-R	2	3	3
Gerson et al. (2001): Control	0.692	5						
Gerson et al. (2001): Treatment	0.984	5						
Geva & Cohen (1987): Overall	1.094	6	Second versus fourth graders: 7 months of Logo instruction versus control (regular computer use in school)	2	Map reading task: Rotate, Start and Turn	2	3	1
Geva & Cohen (1987): Control	0.249	6						
Geva & Cohen (1987): Treatment	0.368	6						
Gibbon (2007)	0.246	3	LEGO Mindstorms Robotics Invention System	3	Raven's Progressive Matrices	1	3	1

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Gillespie (1995): Overall	0.417	6	Engineering graphics course with solid modeling tutorials	2	Paper Folding task, V–K MRT, Rotated Blocks	2	3	3
Gillespie (1995): Control	0.326	2						
Gillespie (1995): Treatment	0.881	3						
Gitimu et al. (2005)	0.698	6	Preexisting fashion design experience: Level of experience based on credit hours		Apparel Spatial Visualization test	2	3	3
Gittler & Gluck (1998): Overall	0.377	2	Training in Descriptive Geometry versus control (no course)	2	3-D cube test	2	1, 2	2
Gittler & Gluck (1998): Control	0.296	2						
Gittler & Gluck (1998): Treatment	0.622	2						
Godfrey (1999): Overall	0.198	3	3-D computer-aided modeling, draw in 2-D and build 3-D models	2	PSVT	2	3	3
Godfrey (1999): Control	0.619	1						
Godfrey (1999): Treatment	0.409	1						
Golbeck (1998): Overall	0.176	6	Fourth versus sixth graders, matched ability versus unmatched-high versus umatched-low versus control (worked alone)	3	WLT	2	3	1
Golbeck (1998): Control	0.304	2						
Golbeck (1998): Treatment	0.528	6						
Goodrich (1992): Overall	0.591	6	Watched training video versus watched placebo video of a cartoon	3	Verticality–Horizontality test	3	3	3
Goodrich (1992): Control	0.734	4						
Goodrich (1992): Treatment	0.917	2						
Goulet et al. (1988): Overall	0.173	1	Those with hockey training versus those without training	3	GEFT	1	2	1
Goulet et al. (1988): Control	0.689	1						
Goulet et al. (1988): Treatment	0.625	1						
Guillot & Collet (2004)	1.582	1	Acrobatic sport training	3	GEFT	1	3	3
Gyanani & Pahuja (1995)	0.317	1	Course lectures plus peer tutoring	2	Spatial geography ability	2	3	1
Hedley (2008)	0.691	4	Course training using geospatial technologies	2	Spatial Abilities test: Map skills	2	3	2
Heil et al. (1998)	0.562	2	Practice group with additional, specific practice versus control (three sessions of mental rotation practice without additional specific practice)	3	Response time mental rotations: Familiar objects in familiar orientations	2	3	3
Higginbotham (1993): Overall	0.770	2	Computer-based versus concrete visualization instruction	3	Middle Grade Mathematics–PSVT (Spatial Visualization), Nonstandardized SVT	2	3	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Higginbotham (1993): Control	0.623	2						
Higginbotham (1993): Treatment	0.597	2						
Hozaki (1987)	1.233	6	Instruction and practice visualizing 2-D and 3-D objects with CAD software	3	Paper Folding task	2	1, 2	3
Hsi et al. (1997)	0.517	4	Pretest versus posttest after strategy instruction using Block Stacking and Display Object software modules with isometric versus orthographic items	3	Paper Folding task, cube counting, matching rotated objects; spatial battery of orthographic, isometric views	2,5	1, 2	3
Idris (1998): Overall	0.916	6	Instructional activities to visualize geometric constructions, relate properties and disembed simple geometric figures	3	Spatial Visualization test, GEFT	1, 2	3	2
Idris (1998): Control	0.340	6						
Idris (1998): Treatment	1.229	6						
Janov (1986): Overall	0.260	6	Instruction in drawing and painting accompanied by artistic criticism	3	GEFT	1	3	3
Janov (1986): Control	0.959	1						
Janov (1986): Treatment	0.470	3						
J. E. Johnson (1991)	0.016	4	Isometric drawing aid versus 3-D rendered model versus animated wireframe versus control (no aid, practice with drawings only)	3	SR–DAT	2	3	3
Johnson-Gentile et al. (1994): Overall	0.544	3	Logo geometry motions unit	3	Geometry motions posttest	2	3	1
Johnson-Gentile et al. (1994): Control	0.239	2						
Johnson-Gentile et al. (1994): Treatment	0.321	1						
July (2001)	0.606	2	Course to teach 3-D spatial ability using Geometer's Sketchpad	2	Surface Development test, MRT	2	3	2
Kaplan & Weisberg (1987)	0.430	2	Pretest versus posttest for third versus fifth graders versus control (no feedback)	3	Purdue Perceptual Screening test (embedded and successive figures)	1	3	1
Kass et al. (1998)	0.501	8	Practice Angle on the Bow task with feedback and read instruction manual versus control (read manual only)	3	Angle on the Bow measure	1	1, 2	3
Kastens et al. (2001)	0.320	2	Training using Where Are We? video game versus control (completed task without assistance)	3	Reality-to-Map (Flag-Sticker) test	2	1, 2	1
Kastens & Liben (2007)	0.791	3	Explaining condition versus control (did not explain sticker placement)	3	Sticker Map task (representational correspondence, errors, offset)	2	3	2

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Keehner et al. (2006): Overall	1.748	1	Learned to use an angled laparoscope (tool used by surgeons)	3	Laproscopic simulation task	1	3	3
Keehner et al. (2006): Control	1.248	1						
Keehner et al. (2006): Treatment	0.547	1						
Kirby & Boulter (1999): Overall	0.125	4	Training in object manipulation and visual imagery versus paper–pencil instruction versus control (test only)	3	Factor-Referenced Tests (Hidden Patterns, Card Rotations, Surface Development test)	5	3	1
Kirby & Boulter (1999): Control	0.055	1						
Kirby & Boulter (1999): Treatment	0.123	2						
Kirchner et al. (1989): Overall	0.976	1	Repeated practice of the GEFT	3	GEFT	1	1	3
Kirchner et al. (1989): Control	0.521	1						
Kirchner et al. (1989): Treatment	0.242	1						
Kovac (1985)	0.166	1	Microcomputer-assisted instruction with mechanical drawing	2	SR–DAT	2	3	2
Kozhevnikov & Thornton (2006): Overall	0.474	16	Added Interactive Lecture Demonstrations to physics instruction for Dickinson versus Tufts science and nonscience majors and middle school and high school science teachers	2, 3	Paper Folding task, MRT	2	3	3
Kozhevnikov & Thornton (2006): Control	0.399	9						
Kozhevnikov & Thornton (2006): Treatment	0.424	9						
Krekling & Nordvik (1992)	1.008	2	Observation training to perform WLT	3	Adjustment error in WLT	3	1	3
Kwon (2003): Overall	1.088	2	Spatial visualization instructional program using Virtual Reality versus paper-based instruction versus control (no training)	3	Middle Grades Mathematics Project Spatial Visualization test	5	3	2
Kwon (2003): Control	0.150	1						
Kwon (2003): Treatment	0.915	2						
Kwon et al. (2002): Overall	0.387	1	Visualization software using Virtual Reality versus control (standard 2-D text and software)	1, 3	Middle Grades Mathematics Project Spatial Visualization test	5	1	2
Kwon et al. (2002): Control	0.521	1						
Kwon et al. (2002): Treatment	0.703	1						
K. L. Larson (1996)	1.423	1	Commentary and movement versus control (no commentary and no movement)	3	View point task (based on Three Mountains)	4	3	1

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
P. Larson et al. (1999)	0.303	2	Repeated Virtual Reality Spatial Rotation training versus control (filler task)	3	V–K MRT	2	1, 2	3
Lee (1995): Overall	0.921	1	Logo training versus control (no Logo training) for second graders	3	WLT	3	3	1
Lee (1995): Control	0.210	1						
Lee (1995): Treatment	0.280	1						
Lennon (1996): Overall	0.280	4	Spatial enhancement course: Spatial visualization and orientation tasks	2	Surface Development test, Paper Folding task, Cube Comparison test, Card Rotation test,	2	3	3
Lennon (1996): Control	0.845	1						
Lennon (1996): Treatment	0.924	1						
Li (2000): Overall	0.314	1	Explanatory statement of physical properties of water versus no explanatory statement	3	Proportion correct on WLT	3	3	1
Li (2000): Control	0.205	1						
Li (2000): Treatment	0.435	1						
Lohman (1988)	0.255	12	Repeated practice mental rotation problems like Shepard–Metzler	3	Paper Folding test, Form Board test, Figure Rotation task, Card Rotation task	2	3	3
Lohman & Nichols (1990): Overall	0.291	4	Train with repeated practice on 3-D MRT: Test on speeded rotation task versus control (test–retest, without the repeated practice)	3	Form Board test, Paper Folding task, Card Rotations, Thurstone's Figures, MRT	2	3	3
Lohman & Nichols (1990): Control	1.039	5						
Lohman & Nichols (1990): Treatment	0.894	4						
Longstreth & Alcorn (1990): Overall	0.677	4	Play with blocks different versus same in color as those used in WPSSI versus control (play with nonblock toys)	3	Block Design, Mazes (both WPPSI subtests)	1, 2	3	1
Longstreth & Alcorn (1990): Control	0.328	2						
Longstreth & Alcorn (1990): Treatment	0.618	4						
Lord (1985): Overall	0.920	4	Imagining planes cutting through solid training versus control (regular biology class with lecture, seminar, and lab)	3	Planes of Reference, Factor-Referenced Tests (Spatial Orientation and Visualization, Flexibility of Closure)	1, 2,5	3	3
Lord (1985): Control	0.057	4						
Lord (1985): Treatment	0.795	4						
Luckow (1984): Overall	0.564	3	Course in Logo Turtle Graphics	2	Paper Form Board test	2	3	3
Luckow (1984): Control	0.480	2						
Luckow (1984): Treatment	0.785	2						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Luursema et al. (2006)	0.465	2	Study 3-D stereoptic and 2-D anatomy stills versus control (study only typical 2-D biocular stills)	3	Identification of anatomical structures and localization of cross-sections in frontal view	1, 2	3	3
Martin (1991)	0.347	3	Learning concept mapping skills for biology	3	GEFT	1	3	2
McAuliffe (2003): Overall	0.642	12	2-D static visuals, 3-D animated visuals, and 3-D interactive animated visuals to display a topographic map	3	Visualizing Topography test	4	1, 2	2
McAuliffe (2003): Control	0.476	6						
McAuliffe (2003): Treatment	0.479	3						
McClurg & Chaillé (1987): Overall	1.157	6	5th versus 7th versus 9th grade: Factory themed versus Stellar 7 mission video games versus control (no video game play)	1	Mental Rotations test	2	3	1, 2
McClurg & Chaillé (1987): Control	0.339	3						
McClurg & Chaillé (1987): Treatment	0.796	6						
McCollam (1997)	0.371	4	Paper folding manipulatives	3	Spatial Learning Ability test	2	3	3
McCuiston (1991)	0.503	1	Computer assisted descriptive geometry lesson with animation and 3-D views versus control (static lessons with text, no animation)	3	V–K MRT	2	3	3
McKeel (1993): Overall	0.047	1	Construct machines and make sketches using LEGO Dacta Technic	2	Paper Folding test	2	1	3
McKeel (1993): Control	0.464	1						
McKeel (1993): Treatment	0.386	1						
Merickel (1992): Overall	0.717	5	Autocade versus Cyberspace spatial skills training	3	SR–DAT, Paper Form Board test, Displacement and Transformation	2	3	1
Merickel (1992): Control	0.612	3						
Merickel (1992): Treatment	0.582	3						
E. A. Miller (1985): Overall	0.076	2	Training in Logo Turtle graphics	3	Eliot–Price Spatial test	4	1, 2	3
E. A. Miller (1985): Control	0.219	2						
E. A. Miller (1985): Treatment	0.262	2						
G. G. Miller & Kapel (1985): Overall	0.468	4	Seventh versus eighth grade gifted versus control (average ability) students trained with problem-solving video game	1	Wheatley Spatial test (MRT)	2	3	1
G. G. Miller & Kapel (1985): Control	0.750	4						
G. G. Miller & Kapel (1985): Treatment	0.939	4						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
J. Miller (1995): Overall	1.026	2	Virtual Reality spatial orientation tests	1	Virtual reality navigation, Spatial Menagerie	4,5	3	1
J. Miller (1995): Control	0.967	1						
J. Miller (1995): Treatment	1.911	1						
R. B. Miller et al (1988): Overall	0.738	1	One academic year of Logo programming	2	Primary Mental Abilities	2	3	1
R. B. Miller et al. (1988): Control	0.136	1						
R. B. Miller et al. (1988): Treatment	0.650	1						
Mohamed (1985): Overall	0.743	2	Logo programming course	2	Developing Cognitive Abilities Test–Spatial, Children's EFT	1, 2	3	1
Mohamed (1985): Control	0.579	2						
Mohamed (1985): Treatment	1.138	2						
Moody (1998)	0.113	1	Strategy instructions for solving mental rotations test	3	V–KMRT	2	3	3
Morgan (1986): Overall	0.408	6	Computer estimation instructional strategy for mathematical simulations	3	Area estimation, length estimation with and without scale	1	1, 2	1
Morgan (1986): Control	0.349	6						
Morgan (1986): Treatment	0.318	6						
Mowrer-Popiel (1991)	0.519	8	Explicit explanation of horizontality principle versus demo of the principle	3	Crossbar and Tilted Crossbar WLT, Spherical and Square Water Bottle task	3	1, 2	3
Moyer (2004): Overall	0.030	1	Geometry course with Geometer's Sketchpad	2	PSVT	2	3	2
Moyer (2004): Control	0.333	1						
Moyer (2004): Treatment	0.444	1						
Mshelia (1985)	1.165	4	Depth perception task and field-independence training	3	Mshelia's Picture Depth Perception task, GEFT	1, 2	3	1
Mullin (2006)	0.392	32	Physical versus cognitive versus no physical control over navigation, with attention versus distracted during wayfinding	3	Wayfinding to target, pointing to target, recalling object locations	1	3	3
Newman (1990): Overall	0.079	2	Educational intervention spread across two consecutive menstrual cycles	3	PMA–SR	2	1	3
Newman (1990): Control	0.251	2						
Newman (1990): Treatment	0.207	2						
Noyes (1997): Overall	1.132	1	Lessons to develop ability to perceive, manipulate, and record spatial information	3	Developing Cognitive Abilities Test-Spatial	2	3	1
Noyes (1997): Control	0.080	1						
Noyes (1997): Treatment	0.880	1						
Odell (1993): Overall	−0.392	2	Earth Science course with or without 3-D laboratory models	2	Surface Development test, Paper Folding task	2	3	2
Odell (1993): Control	0.175	2						
Odell (1993): Treatment	0.042	2						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Okagaki & Frensch (1994): Overall	0.643	6	Tetris video game training versus control (no video game)	1	Form Board test, Card Rotation test, Cube Comparison test (from French kit)	2	1, 2	3
Okagaki & Frensch (1994): Control	0.239	6						
Okagaki & Frensch (1994): Treatment	0.420	6						
Olson (1986): Overall	0.523	6	Geometry course supplemented with computer-assisted instruction in geometry or Logo training	2	Monash Spatial Visualization test	2	1, 2	1
Olson (1986): Control	0.819	4						
Olson (1986): Treatment	0.622	2						
Ozel et al. (2002)	0.330	6	Gymnastics training	3	Shepard–Metzler MRT (response time and rotation speed)	2	2	3
Pallrand & Seeber (1984): Overall	0.679	15	Draw scenes outside, locate objects relative to fictitious observer, reorientation exercises, geometry lessons	3	Paper Folding test, Surface Development test, Card Rotation test, Cube Comparison test, Hidden Figures test	1, 2	3	3
Pallrand & Seeber (1984): Control	0.330	15						
Pallrand & Seeber (1984): Treatment	0.831	5						
Parameswaran (1993): Overall	0.633	30	Interactive and rule training on horizontality task	3	Water Clock verticality and horizontality score, Crossbar test, Verticality test, Water Bottle test	3	1, 2	3
Parameswaran (1993): Control	0.354	4						
Parameswaran (1993): Treatment	0.790	2						
Parameswaran (2003)	0.870	40	Ages 5,6,7,8,9: Graduated training versus demonstration training versus control (completed task with no feedback)	3	WLT, Verticality task	3	1, 2	1
Parameswaran & De Lisi (1996): Overall	0.703	16	Tutor-guided direct instruction in principle versus learner-guided self-discovery versus control (no feedback)	3	Van Verticality test, Water Clock and Cross-Bar tests of horizontality, WLT	3	1, 2	3
Parameswaran & De Lisi (1996): Control	0.103	2						
Parameswaran & De Lisi (1996): Treatment	0.525	4						
Pazzaglia & De Beni (2006)	0.386	4	Repeated practice through four learning phases	3	Map reading and pointing task	4	3	3
Pearson (1991): Overall	0.301	3	Intensive introductory film production course	2	SR–DAT	2	3	3
Pearson (1991): Control	0.748	3						
Pearson (1991): Treatment	0.482	3						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Pennings (1991): Overall	0.532	12	Conservation of horizontality training and restructuring in perception training	3	WLT, diagnostic EFT	1, 3	1, 2	1
Pennings (1991): Control	0.336	8						
Pennings (1991): Treatment	0.465	4						
Pérez-Fabello & Campos (2007)	1.397	4	Years of training in artistic skills (academic year used to approximate)	3	Visual Congruence - SR, Spatial Representation test	4	3	3
Peters et al. (1995): Overall	0.118	1	Repeated practice once a week for 4 weeks	3	V–K MRT	2	1	3
Peters et al. (1995): Control	3.683	1						
Peters et al. (1995): Treatment	3.558	1						
Philleo (1997)	0.154	1	Produced 2-D diagram from 3-D view with Microworlds virtual reality or paper and pencil	3	Author created Where Am I Standing? task	4	3	1
Piburn et al. (2005)	0.539	3	Computer-enhanced geology module versus control (regular geology course with standard written manuals)	3	Surface Development test: Visualization and Orientation (Cube Rotation test)	2	3	3
Pleet (1991): Overall	0.086	6	Transformational geometry training with Motions computer program or hands-on manipulatives	3	Card Rotations test	2	1, 2	2
Pleet (1991): Control	0.568	4						
Pleet (1991): Treatment	0.501	2						
Pontrelli (1990): Overall	0.783	1	TRACON (Terminal Radar Approach Control) computer simulation	3	Author created spatial perception test based on exam for air traffic controllers	1	3	3
Pontrelli (1990): Control	0.116	1						
Pontrelli (1990): Treatment	0.887	1						
Pulos (1997)	0.662	3	Demonstration of WLT without description of the phenomenon	3	WLT	3	3	3
Qiu (2006): Overall	0.351	9	College course in different geographic information technologies	2	Author created tests: Spatial Visualization, Spatial Orientation, Spatial Relations	2, 4	3	3
Qiu (2006): Control	0.181	3						
Qiu (2006): Treatment	0.143	9						
Quaiser-Pohl et al. (2006)	0.084	6	Preference for video games: Action and simulation versus logic and skill versus nonplayers	1	V–K MRT	2	1, 2	2
Rafi et al. (2008)	0.737	6	Virtual environment training	3	Author created test of assembly and transformation	2	1, 2	2
Ralls (1998)	0.577	1	Computer-based instruction in logical and spatial ability tasks	3	Paper Folding task	2	3	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Robert & Chaperon (1989): Overall	0.656	12	Watched videotape demonstration of correct responses to WLT, with and without discussion	3	WLT–Acquisition, WLT–Proximal Generalization	3	3	3
Robert & Chaperon (1989): Control	0.428	4						
Robert & Chaperon (1989): Treatment	0.997	8						
Rosenfield (1985): Overall	0.304	1	Exercise in spatial visualization and rotation	3	CAPS–SR	2	2	2
Rosenfield (1985): Control	0.759	1						
Rosenfield (1985): Treatment	0.454	1						
Rush & Moore (1991)	0.366	6	Restructuring strategies, finding hidden patterns, visualizing paper folding, finding path through a maze	3	Paper Folding task, GEFT	1, 2	3	3
Russell (1989): Overall	0.171	18	Mental rotation practice with feedback	3	V–K MRT, Depth Plane Object Rotation test, Rotating 3-D Objects test	2	1, 2	3
Russell (1989): Control	0.491	12						
Russell (1989): Treatment	0.463	6						
Saccuzzo et al. (1996)	0.609	4	Repeated practice on computerized and paper-and-pencil tests	3	Surface Development test, Computerized Cube test, PMA Space Relations test, Computerized MRT	2	3	3
Sanz de Acedo Lizarraga & García Ganuza (2003): Overall	1.244	2	Mental rotation training worksheet versus control (regular math course)	3	SR–DAT (visualization and mental rotation)	2	3	2
Sanz de Acedo Lizarraga & García Ganuza (2003): Control	0.256	2						
Sanz de Acedo Lizarraga & García Ganuza (2003): Treatment	0.791	2						
Savage (2006)	0.723	6	Repeated practice using virtual reality to traverse a maze	3	Time required to traverse each tile of maze	1	3	3
Schaefer & Thomas (1998)	0.828	2	Repeated practice on rotated EFT	3	Gottschaldt Hidden Figures, EFT	1	1, 2	3
Schaie & Willis (1986)	0.417	3	Spatial training versus control (inductive reasoning training)	3	Alphanumeric rotation, Object rotation, PMA–Spatial Orientation	2	3	3
Schmitzer-Torbert (2007): Overall	0.699	8	Place versus response learning of transfer target versus control (training target)	3	Percent correct and route stability on maze learning for first versus last trial	1	1, 2	3
Schmitzer-Torbert (2007): Control	0.882	8						
Schmitzer-Torbert (2007): Treatment	1.645	8						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Schofield & Kirby (1994)	0.491	12	Area (restricted search space) versus area and orientation provided, versus spatial training (identify features and visualize contour map) versus verbal training (verbalize features) versus control (no instructions)	3	Location time to mark placement on map, Surface Development test, Card Rotations (S-1 Ekstrom kit of Factor-Referenced Cognitive Tests)	2	2	3
Scribner (2004)	0.126	4	Drafting instruction tailored to students	2	PSVT	2	3	3
Scully (1988): Overall	0.058	1	Computer-aided design and manufacturing 3-D computer graphics design	3	Guilford–Zimmerman 3-D Visualization	2	3	3
Scully (1988): Control	0.469	1						
Scully (1988): Treatment	0.571	1						
Seddon & Shubber (1984)	0.758	9	All versus half colored slides versus monochrome slides shown simultaneously versus cumulatively versus individually versus control	3	Rotations test (author created)	2	2	2
Seddon & Shubber (1985a)	1.886	36	13–14, 15–16, versus 17–18 year-olds, with 0, 6, 9,15 or 18 colored structures, with and without 3, 6, or 9 diagrams	3	Mental rotations test (author created)	2	2	2
Seddon & Shubber (1985b)	0.995	18	Ages 13–14 and 15–16 versus 17–18	3	Framework test, Cues test–Overlap, Angles, Relative Size, Foreshortening; mental rotation (author created)	2	2	2
Seddon et al. (1984)	1.742	24	Diagrams versus shadow-models-diagrams versus models-diagrams training for those failing 1, 2, 3, or 4 cue tests. Compared 10° versus 60°, abrupt versus dissolving, diagram change for children remediated in Stage 1 versus control (no remediation)	3	Mental rotations test (author created)	2	2	3
Sevy (1984)	1.008	7	Practice with 3-D tasks on Geometer's Sketchpad	3	Paper Folding task, Paper Form Board test, V–K MRT, Card Rotations test, Cube Comparison test, Hidden Patterns test, CAB–Flexibility of Closure	1, 2	3	3
Shavalier (2004): Overall	0.211	3	Trained with Virtus Walkthrough Pro software versus control group (no treatment)	3	Paper Folding test, Eliot–Price test (adaptation of Three Mountains), V–K MRT	2, 4	3	1

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Shavalier (2004): Control	0.435	3						
Shavalier (2004): Treatment	0.491	3						
Shubbar (1990)	2.260	6	3- versus 6- versus 30-s rotation speed, with or without shadow	3	Mental rotations test (author created)	2	2	2
Shyu (1992)	−0.686	1	Origami instruction and prior knowledge	3	Building an Origami Crane	2	3	3
Simmons (1998): Overall	0.359	3	Took pretest and posttest on both visualization and GEFT versus only visualization versus no visualization (GEFT posttest only)	3	Visualization test, GEFT	1, 2	3	3
Simmons (1998): Control	0.565	1	Self-paced instruction booklet in orthographic projection versus control (professor-led discussion of professional issues)	3	Visualization test, GEFT	1, 2	3	3
Simmons (1998): Treatment	0.646	1						
Sims & Mayer (2002): Overall	0.316	9	Tetris players versus non-Tetris players versus control (no video game play)	1	Paper Folding test, Form Board and MRT (with Tetris versus non-Tetris shapes or letters), Card Rotations test	2	1	3
Sims & Mayer (2002): Control	1.111	9						
Sims & Mayer (2002): Treatment	1.193	9						
G. G. Smith (1998): Overall	−0.630	1	Active (used computer) versus passive participants (watched actives use the computer)	3	Visualization puzzles, polynomial assembly	2	2	1
G. G. Smith (1998): Control	0.220	1						
G. G. Smith (1998): Treatment	−0.254	1						
G. G. Smith et al. (2009): Overall	0.330	8	Solving interactive Tetromino problems	2, 3	Accuracy on visualization puzzles	2	1	3
G. G. Smith et al. (2009): Control	0.360	8						
G. G. Smith et al. (2009): Treatment	0.483	8						
J. P. Smith (1998)	1.037	3	Instruction in chess	2	Guilford–Zimmerman tests of Spatial Orientation and Spatial Visualization, GEFT	1, 2, 4	3	2
J. Smith & Sullivan (1997)	0.380	1	Instruction in chess	3	GEFT	1	3	2
R. W. Smith (1996)	0.506	2	Animated versus nonanimated feedback	3	Author created MRT (accuracy and response time)	2	3	3
Smyser (1994): Overall	0.166	3	Computer program for spatial practice	2	Card Rotations test	2	3	2
Smyser (1994): Control	1.502	3						
Smyser (1994): Treatment	1.688	3						
Snyder (1988): Overall	0.274	2	Training to increase field independence	3	GEFT	1	3	3
Snyder (1988): Control	1.207	2						
Snyder (1988): Treatment	0.851	2						
Sokol (1986): Overall	0.319	1	Biofeedback-assisted relaxation	3	EFT	1	3	3
Sokol (1986): Control	0.135	1						
Sokol (1986): Treatment	0.431	1						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Sorby (2007)	1.718	9	Pretest versus posttest scores for those in initial spatial skills course (one quarter) or those in multimedia software course (one semester)	2	Mental Cutting test, SR–DAT, PSVT–Rotation	2	3	3
Sorby & Baartmans (1996)	0.926	1	Freshman engineering students (male and female)	2	PSVT–Rotation, score and identify 3-D irregular solid in a different orientation	2	3	3
Spangler (1994)	0.573	30	Computer lesson converting 3-D objects to 2-D and 2-D objects to 3-D, mental rotation of 3-D objects	3	2-D Sketching, 3-D Sketching, MRT	2	3	3
Spencer (2008): Overall	−0.005	10	Practice with physical, digital, or choice of physical or digital geometric manipulatives	3	Test of Spatial Visualization in 2-D Geometry, Wheatley Spatial Ability test	2	3	3
Spencer (2008): Control	0.463	2						
Spencer (2008): Treatment	0.191	6						
Sridevi et al. (1995): Overall	0.967	2	Yoga practice	3	Perceptual Acuity test, GEFT	1	3	3
Sridevi et al. (1995): Control	−0.110	2						
Sridevi et al. (1995): Treatment	0.626	2						
Stewart (1989)	0.381	3	Lecture on map interpretation, terrain analysis	3	Map Relief Assessment exam	5	3	3
Subrahmanyam & Greenfield (1994)	2.176	2	Playing spatial video game Marble Madness versus control (quiz show game Conjecture)	1	Computer-based test of dynamic spatial skills	1	1, 2	1
Sundberg (1994)	1.143	4	Spatial training with physical materials and geometry instruction	3	Middle Grades Mathematics Project	5	3	2
Talbot & Haude (1993)	0.416	3	Experience with sign language		MRT	2	1	3
Terlecki et al. (2008): Overall	0.305	6	Playing Tetris along with repeated practice versus control (repeated practice only)	1, 3	Paper Folding task, Surface Development test, Guilford–Zimmerman Clock task, MRT	2	1, 2, 3	3
Terlecki et al. (2008): Control	0.629	6						
Terlecki et al. (2008): Treatment	0.852	6						
Thomas (1996): Overall	0.299	2	3-D CADD instruction versus control (2-D CADD instruction)	2	Cube rotation (author created)	2	2	3
Thomas (1996): Control	0.745	2						
Thomas (1996): Treatment	1.074	2						
Thompson & Sergejew (1998)	0.380	2	Practice of the WAIS–R Block Design test, MRT	3	WAIS–R Block Design test, MRT	2	3	3
Thomson (1989)	0.442	3	Transformational geometry and mapping computer programs	3	Map Relief Assessment test	4	3	1

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Tillotson (1984): Overall	0.762	3	Classroom training in spatial visualization skills	2	Punched Holes test, Card Rotation test, Cube Comparison test	2	3	1
Tillotson (1984): Control	0.127	3						
Tillotson (1984): Treatment	0.667	3						
Tkacz (1998)	−0.063	12	Map Interpretation and Terrain Association Course	2	Perspective Orientation, Shepard–Metzler MRT, 2-D Rotation, GEFT	1, 2, 4	3	3
Trethewey (1990): Overall	0.481	4	Paired with partner versus control (worked alone): High versus mid versus low scorers on Flexibility of Closure posttest within the treatment group	3	MRT, Flexibility of Closure	1, 2	3	3
Trethewey (1990): Control	0.604	4						
Trethewey (1990): Treatment	0.591	3						
Turner (1997): Overall	0.141	8	CAD mental rotation training using same or different, old or new item types, for Cooper Union versus Penn State engineering students versus control (standard wireframe CAD)	3	V–K MRT	2	1, 2	3
Turner (1997): Control	0.117	8						
Turner (1997): Treatment	0.219	8						
Ursyn-Czarnecka (1994): Overall	0.037	1	Geology course with computer art graphics training	2	V–K MRT	2	3	3
Ursyn-Czarnecka (1994): Control	0.154	1						
Ursyn-Czarnecka (1994): Treatment	0.169	1						
Vasta et al. (1996)	0.214	4	Self-discovery (problems ranked in difficulty and competing cues) versus control (equal practice with nonranked problem set)	3	WLT, Plumb-Line task	3	1, 2	3
Vasu & Tyler (1997): Overall	0.216	3	Course training using Logo	2	Developing Cognitive Abilities test–Spatial	2	3	1
Vasu & Tyler (1997): Control	0.577	2						
Vasu & Tyler (1997): Treatment	0.488	1						
Vazquez (1990): Overall	0.459	1	Training on spatial visualization with the aid of a graphing calculator	3	Card Rotations test	2	3	2
Vazquez (1990): Control	0.325	1						
Vazquez (1990): Treatment	0.852	1						
Verner (2004)	0.532	6	Practice with RoboCell computer learning environment	3	Spatial Visualization test, MRT, Spatial Perception test (all author designed and Eliot & Smith)	1, 2	3	2
Wallace & Hofelich (1992)	1.073	3	Training in geometric analogies	3	MRT (accuracy and response time)	2	3	3
Wang et al. (2007): Overall	0.389	1	3-D media presenting interactive visualization exercises showing different perspectives, manipulation and animation of objects versus control (2-D media)	3	Purdue Visualization of Rotation test	2	3	3
Wang et al. (2007): Control	−0.211	1						
Wang et al. (2007): Treatment	0.080	1						

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Werthessen (1999): Overall	1.282	4	Hands-on construction of 3-D figures	2	SR–DAT, V–K MRT	2	1, 2	1
Werthessen (1999): Control	0.32	4						
Werthessen (1999): Treatment	1.345	4						
Wideman & Owston (1993)	0.229	3	Weather system prediction task	2	SR–DAT	2	3	2
Wiedenbauer & Jansen-Osmann (2008)	0.506	2	Manually operated rotation of digital images	3	Author created computerized MRT (accuracy and response time)	2	3	1
Wiedenbauer et al. (2007): Overall	0.462	16	Virtual Manual MRT training with joystick versus control (play computer quiz show game). Compared rotations of 22.5°, 67.5°, 112.5°, 157.5°	3	V–K MRT (response time, errors)	2	1, 2	3
Wiedenbauer et al. (2007): Control	0.245	16						
Wiedenbauer et al. (2007): Treatment	0.373	16						
Workman et al. (1999)	1.015	2	Training in clothing construction and pattern making versus control (no training)	2	Apparel Spatial Visualization test (author created), SR–DAT	2	1	3
Workman & Lee (2004)	0.373	2	Flat pattern apparel training	2	Apparel Spatial Visualization test (author created), Paper Folding task	2	3	3
Workman & Zhang (1999)	1.937	4	CAD versus manual pattern making versus control (course in CAD instead of Pattern making)	2	Apparel Spatial Visualization test (author created), Surface Development test	2	3	3
Wright et al. (2008): Overall	0.373	12	Practice versus transfer on MRT or Paper Folding task	3	Mental Paper Folding task and MRT response time, slope, intercept, errors	2	3	3
Wright et al. (2008): Control	1.201	12						
Wright et al. (2008): Treatment	0.581	12						
Xuqun & Zhiliang (2002)	0.619	4	Cognitive processing of image rotation tasks	3	MRT (accuracy and response time), Assembly and Transformation task (accuracy and response time)	2	2	3
L. G. Yates (1986)	0.619	2	Spatial visualization training versus control (no training)	3	Paper Folding task, Cube Comparison test	2	2	3
B. C. Yates (1988)	0.490	2	Computer-based teaching of spatial skills	3	DAT	2	3	2
Yeazel (1988)	0.869	8	Air Traffic Control task, repeated practice	3	Angular Error on the Air Traffic Control task	1	3	2
Zaiyouna (1995)	1.754	3	Computer training on MRT	3	V–K MRT, Accuracy and Speed	2	1, 2, 3	3

(*Appendices continue*)

Appendix C (*continued*)

Study	*g*	*k*	Training description	Training category[a]	Outcome measure	Outcome category[b]	Sex[c]	Age[d]
Zavotka (1987): Overall	0.597	9	Animated films of rotating objects changing from 3-D to 2-D	3	Orthographic drawing task, V–K MRT	2	3	3
Zavotka (1987): Control	−0.048	1						
Zavotka (1987): Treatment	0.523	3						

Note. CAD = computer-aided design; CADD = computer-aided design and drafting; CAPS-SR = Career Ability Placement Survey-Spatial Relations subtest; DAT = Differential Aptitude Test; EFT = Embedded Figures Test; GEFT = Group Embedded Figures Test; PMA-SR = Primary Mental Abilities-Space Relations; PSVT = Purdue Spatial Visualization Test; RFT = Rod and Frame Test; SR-DAT = Spatial Relations-Differential Aptitude Test; STAMAT = Schaie-Thurstone Adult Mental Abilities Test; V-K MRT = Vandenberg-Kuse Mental Rotation Test; WAIS-R = Wechsler Adult Intelligence Scale-Revised; WISC = Wechsler Intelligence Scale for Children; WLT = Water-Level Task; WPPSI = Wechsler Preschool and Primary Scale of Intelligence.

[a] 1 = video game; 2 = course; 3 = spatial task training.

[b] 1 = intrinsic, static; 2 = intrinsic, dynamic; 3 = extrinsic, static; 4 = extrinsic, dynamic; 5 = measure that spans cells.

[c] 1 = female; 2 = male; 3 = not specified.

[d] 1 = under 13 years; 2 = 13–18 years; 3 = over 18 years.

[e] Sex not specified for control and treatment groups.

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