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The Psychology of Practice: Lessons From Spatial Cognition

David H. Uttal and Nathaniel G. Meadow

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[–] Abstract and Keywords

Having high levels of spatial skills strongly predicts attainment in science, technology, engineering, and mathematics fields (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). The focus of this chapter is on two issues: (a) the effect of training and practice on spatial skills and (b) the cognitive mechanisms that support training-related improvement. We discuss a recently conducted meta-analysis that measures the beneficial effects of practice on spatial ability. On average, training led to an improvement of almost one-half standard deviation. Moreover, in some cases the training-related improvements were durable and transferred to other spatial tasks. Research on the effects of training on one well-known spatial task, mental rotation, has led to specific accounts of the influence of practice and training. Finally, we review the effects of video games on spatial skills and their potential impact on spatial cognition. The ability to improve people's spatial ability provides an avenue to increase participation in mathematics, science, and engineering.

Keywords: spatial skills, practice, STEM, transfer, sex differences

The ability to think about and communicate spatial information is critically important to human learning. Spatial cognition is important not only in everyday tasks such as navigation but also in thinking about scientific and mathematical information. Several studies (e.g., Humphreys, Lubinski, & Yao, 1993; Wai et al., 2009) have documented that skill in spatial tasks strongly predicts academic attainment in science, technology, engineering, and mathematics (*STEM*) fields. There is great interest in increasing the number of Americans capable of studying and ultimately obtaining jobs in STEM fields, and spatial practice and training may be one way (of many) (see Sorby, 2009; Spence & Feng, 2010; Terlecki, Newcombe, & Little, 2008; Uttal & Cohen, 2012) to increase STEM attainment.

For all of these reasons, it is critically important to determine how spatial thinking can be improved. Until now, researchers have disagreed substantially on basic questions such as whether, and to what extent, spatial cognition responds to practice and training. Although some researchers have claimed that spatial cognition is highly malleable, others have suggested either that training has no effect or is limited to specific tasks that are similar to the trained tasks (see Uttal et al., 2012). Our goal here is to address these issues by reviewing and systematizing what is known about the influences of practice and training on spatial thinking. We also point out reasons why previous researchers have reached different conclusions regarding the influences of practices, and we attempt to resolve some of these disagreements.

In addition to its importance for improving spatial cognition, investigating the effects of practice on spatial thinking can also shed light on more general issues in cognition. The study of practice is one of the oldest topics in psychology. Even before 1900, researchers were conducting detailed and specific studies of the effect of practice on learning (p. 875) specific skills, such as Morse code (Bryan & Harter, 1897, 1899). More recently, research on the effects of practice has figured prominently in studies of expertise, with many findings indicating it can take years of intensive practice to acquire a high level of competency in domains ranging from musical performance to chess (e.g., Ericcsson, Krampe, & Tesch-Römer, 1993). However, despite the large amount of research that has been conducted on this topic, it is still not easy to answer some fundamental questions regarding the effects of practice. What happens, at a perceptual and cognitive level, when people practice? How do underlying mental representations and processes change with practice? The research discussed next reveals that studying the effects of practice on spatial cognition can shed light on these issues. In several cases (e.g., mental rotation) the cognitive mechanisms that are involved have been well specified, and this work can provide a foundation for understanding the influences of practice. Reviewing this literature can provide insights into whether, and why, spatial thinking is malleable and how it responds to practice and training.

Organization and Definitions

This chapter is organized as follows: We begin by defining spatial cognition and practice. We then provide reviews of work on spatial training and practice, including both a systematic meta-analysis and a more detailed, focused narrative review of the mechanisms of improvement in two well-known tasks and training paradigms (mental rotation and video game playing). Finally we consider the implications of our findings and highlight important research questions that need to be addressed.

Defining Spatial Cognition

We define spatial cognition as the representation and transformation of a set of objects in space, or the relations among a set of objects (Uttal & Cohen, 2012). One complication is that there are many different kinds of spatial tasks, and different tasks may respond differently to practice. Defining the individual components of spatial cognition and the underlying cognitive skills or abilities that support these operations has proved to be a challenging task. There is very little agreement (and relatively little psychometric coherence) to the different measures of spatial cognition (Carroll, 1993; Eliot, 1987; Hegarty & Waller, 2005; Lohman, 1988).

The most successful approach to defining the divisions of spatial skills involves a combination of factor-analytic methods and analysis of the cognitive skills and processes that correlate with these factors (see Hegerty & Waller, 2005; Linn & Petersen, 1985; Miyake & Shah, 1999; Uttal et al., 2012). The largest and most consistent factor is *spatial visualization* (Linn & Petersen, 1985), which is the ability to transfer and mentally manipulate representations of objects. A second factor that has shown up in several psychometric studies is sometimes called *spatial memory* (Ekstrom, French, & Harman, 1979), which may include both recognizing and recalling spatial figures and relations.

We also note that specific tasks may involve many steps that tap into different skills. For example, mental rotation not only requires the transformation of spatial information but also the encoding, activation, and recall of the relevant figures. In addition, practice in one kind of skill may transfer to tasks in another skill. For example, the gains from practicing mental rotation may not be limited to the specific dynamics of turning the object over in one's mind. People may also improve at recognizing and representing particular shapes, and hence decisions regarding whether a stimulus is a mirror image of the target may become faster and more accurate.

Defining Practice

What is practice? What distinguishes practice from other, related activities, such as learning, repetition, and performance? We suggest that practice has two distinguishing characteristics. First, it is intensive; it involves a substantial amount of attention and time. In contrast, performance is not practice, as it typically is not intensive enough to provide the desired outcomes. For example, Ericsson, Krampe, and Tesch-Römer (1993) point out that the average baseball player will see only about 15 pitches in a typical performance—a professional game—but the same baseball player may see hundreds of pitches daily in batting practice.

Note that practice does not need to occur in a single session or single location. Indeed, many studies have now established that practice works best when it is *distributed* across time (e.g., Mumford, Constanza, Baughman, Threlfall, & Fleishman, 1994). Yet, even in the shorter, distributed practice sessions, the participant typically works at the task repeatedly. One-trial learning is not practice; skills or abilities that are acquired without repetition do not require practice.

Second, practice usually involves the same or similar tasks, or at least tasks within the same general domain. The range of skills demanded in that (p. 876) domain determine how much practice is required to obtain a level of expertise or mastery. Well-defined or constrained tasks may improve dramatically with relatively little practice, whereas 10,000 or more hours of practice is typically required to obtain a degree of mastery in highly complex domains, such as chess or music (e.g., Gladwell, 2008; Ericsson & Smith, 1991).

It is also important to point out that the gains from practice are not always available to conscious awareness; the effects of practice can often be implicit in nature. A good example is what may happen as one plays a spatially challenging video game. People practice the video game and are aware that they are improving; however, they may not be aware of the *cause* of this improvement (e.g., Gee, 2003). Playing action video games may in fact facilitate more general abilities, such as the capacity of video-spatial attention, and these improvements facilitate not only playing of the specific video game but also performance on a host of cognitive and psychometric spatial ability tasks. Likewise, people who practice classic implicit motor learning tasks, such as mirror-tracing, may improve dramatically without knowing precisely why or what they have learned. Our review includes literature both on explicit and implicit practice.

Quantitative and Qualitative Reviews of Research on the Effects of Practice on Spatial Thinking

In this chapter we review literature investigating the effects of spatial practice and training at two complementary levels. The first is broad, course, and quantitative; we present the results of a meta-analysis of the effects of spatial training and practice on a wide variety of outcome measures. The meta-analysis provides a measure of the overall effectiveness of spatial training and practice. It also identifies several factors that may contribute to the large differences in prior findings and claims. Our second approach is more fine and qualitative; we present a narrative review and analysis of the causes of practice-related improvement in mental rotation and video game playing.

Each approach has both advantages and disadvantages. The meta-analysis provides a very accurate measure of the overall effectiveness of spatial training and practice, but it does not provide much information about the mechanisms through which these effects occur. The narrative review provides a much more focused account of the influences of practice and training, but it is limited to only to two domains that are well established or of great current interest. When taken together, the two approaches provide a reasonably comprehensive account of both whether, and how, spatial practice and training improve spatial thinking.

Meta-Analysis of Spatial Practice and Training Studies

We recently completed a meta-analysis of the large literature on spatial training and practice (Uttal et al., 2012). We were interested in whether practicing spatial tasks led to improvements in performance and, if so, whether these effects endured over time and whether they transferred to different, untrained tasks. The issue of transfer is particularly important because direct training in spatial tasks will not lead to improvements in STEM unless the knowledge that is gained transfers to other, untrained tasks.

Method

Selecting and Finding Articles

A critical issue in any meta-analysis is the literature search. We sought to provide a comprehensive yet focused review of the literature. We therefore chose to focus on a 25-year period of research, from 1984 through 2009. We searched for relevant literature in digital databases (PsycInfo, ERIC, and ProQuest Dissertations and Theses). We also contacted researchers in the field. We took pains to obtain as much unpublished work as possible. In this regard, the database ProQuest Dissertations and Theses proved to be particularly important as it focuses on dissertations, many of which remain unpublished.

We read the abstracts of all articles that met our criteria. If the study could not be immediately eliminated, we read the full paper. Reliability of these judgments was high, and disagreements were resolved through consensus. In the end, we included over 200 papers, and most studies reported multiple experiments or manipulations. The range of practice and training varied widely from intensive, laboratory-based studies to examination of the effects of more real-world practice opportunities, such as the influences of taking a spatially demanding geology course (e.g., Pibrum, Reynolds, McAuliffe, Leedy, & Birk, 2005).

Conversion to Effect Sizes

After deciding that a given article should be included, we then converted the findings to a standard effect size. By expressing observed differences in terms of standard deviation units, effect sizes (p. 877) provide a means of comparing studies despite differences in dependent measures. In this case, the effect size usually involved comparisons of treatment and control groups, as well as comparisons of both groups before and after training.

Results

Overall Results

The results indicate that spatial skills respond strongly to practice or training. The overall effect size was 0.47 (*SE* = 0.04).[1] Spatial training and practice improved performance by almost one-half of a standard deviation.

Duration of Effects

The effects of training and practice are only useful if they last. People will not be able to engage in intense practice forever, so its effects need to endure for it to be of practical use. One of the continuing concerns about attempts to improve spatial reasoning is that the effects are often fleeting (e.g., National Research Council, 2006). However, our comprehensive meta-analysis does provide evidence that the effects of spatial training can endure. In those studies that did include delays, the effects of training were as strong after the delay as immediately after practice or training. One challenge in interpreting this finding is that many studies did not include measures of the effects of practice after delay. In the typical laboratory study, for example, measures are typically taken only during one sitting, and the entire process often lasts less than an hour. Nevertheless, those that did include delays found, on average, that the effects of practice or training can last.

Transfer

For practice and training to be effective, they also need to transfer to other tasks that are not included in the practice or the training. Moreover, as discussed earlier, the issue of transfer has very important implications for understanding the cognitive changes that occur as a result of practice. Therefore, we paid particular attention to whether practice on one task transferred to other tasks that were not explicitly included in the training or practice. As in the analysis of the duration of effects, our analyses are somewhat limited by researchers' self-selection regarding whether to study transfer. Most researchers did not include a transfer task. However, those studies that did look for transfer usually found it. In fact, the overall effect size for those studies that tested for transfer was also about one-half of a standard deviation improvement.

Moderators

We examined several factors that have been shown, or thought, to influence the magnitude of training effects on spatial thinking, including study design, as well as participants' sex and age.

Study Design and Control Group Performance

Different researchers used different experimental designs, and these differences substantially affected the findings. There were three main kinds of experimental design. In a *between-subjects* only design, the researcher randomly assigns participants to an experimental or control group. The experimental group receives training or practices specific tasks that are designed to enhance some kind of spatial performance. Performance is measured only after the training or practice is implemented. Thus, between-subjects only designs do not include a pretest. Conversely, in a *within-subjects* only design, performance is measured both before (pretest) and after (posttest) training or practice. However, there is no control group, only one group is assessed. Finally, the most common design, *mixed designs*, combines elements of both; participants are assigned to an experimental or control group, and their performance is measured both before and after training or practice. Approximately two-thirds of the studies in our meta-analysis used the mixed design.

Experimental design affected the magnitude of the reported effects. Studies using the within-only design found significantly higher effects of training than studies that used the between-only or mixed design. This result is not surprising because within-subjects designs do not include a control group; thus, all of the improvement may be attributed to the effects of practice. However, this assumption is methodologically unsound because we know that simply taking a test more than once often leads to improved performance on that test. The magnitude of the test-retest effects can be substantial, and at least part of the larger improvement in studies that used the within-only design can be attributed to the confounding of improvement due to practice or training on the relevant spatial test or ability and the general improvement that would be expected simply from tasking a test. This issue is discussed further later.

Control Group Performance

To further examine the influences of control groups on overall findings, we separated the control and treatment groups for independent analysis. Note that this analysis was only possible for the (p. 878) mixed design studies, as only this design includes both a control and treatment group, and measures taken both before and after training or practice.

Two aspects of this analysis were noteworthy. First, the treatment groups (g = 0.62, SE = 0.04)[2] improved significantly more than the control groups did (g = 0.45, SE = 0.04), $p < .01$. Second, the magnitude of the control group improvement was surprisingly high. Studies of test-retest effects in other domains have found effect sizes of approximately half the value of the mean-weighted effect size in our control groups (Hauschknecht, Halpert, Di Paolo, & Gerrard, 2007). The high levels of improvement in the control groups have important implications for understanding why different researchers have reached such different conclusions regarding the effectiveness of training and practice.

We suggest that differences in the reported effect sizes and statistical significance of a given study may depend not only on whether there was a control group but also on what the control group did. As shown earlier, the absence of a control group produced significantly larger findings in studies measuring improvement due to practice or training. In the same vein, a highly performing control group could *suppress* the overall finding of a study by rivaling the gains demonstrated by the experimental group.

A very good example of the importance of considering the improvement in control groups comes from the research of Sims and Mayer (2002). They investigated the influences of playing the video game Tetris on participants' performance on a battery of nine spatial ability tests. Experiment 1 was correlational, focusing on differences between people who already played or did not play Tetris frequently. Experiment 2 used an experimental design to investigate the influences of practicing Tetris on the performance on the spatial battery of tests. We focus only on the second experiment here.

The participants in Experiment 2 were 16 women who had no experience playing Tetris. Half of them were assigned to receive 14 sessions of approximately 1-hour practice in playing Tetris, and the other half were assigned to a control question. Both the experimental and control groups took the same tests, completing various measures of spatial ability at sessions 1, 2, 5, 9, and 15. Thus, the only difference between the control and experimental groups was the Tetris training; both groups took the same tests at the same time throughout the practice period.

The training group improved substantially, with a mean effect size of 1.19. However, despite this very large effect, the comparison to the control group did not reach statistical significance. Why? The answer is that the control group also improved greatly, with a mean effect size of 1.11. Based on these results, Sims and Mayer (2002) concluded that training effects are not large or even statistically significant, if comparisons are made with the appropriate control group. They wrote that

> …participants in both groups showed large pretest-to-posttest improvements for all the measures… However, there were no significant main effects for group, nor were there any significant interactions between group and time of test. Thus, there is no evidence that up to 12 hours of Tetris playing had any effect on students' spatial ability skills beyond merely retaking the tests.

We reinterpret these results in a different light. Although it is true that there were no significant differences between the training and control group, the fact that both groups improved so much is remarkable. Whereas Sims and Mayer interpreted the results as indicating that spatial skills do not respond well to training or practice, our analysis leads to the opposite conclusion: Spatial skills respond very well to training or practice, and importantly, this training may take the form of either direct or implicit practice (or both). We suggest that the experience of taking multiple tests throughout the experiment was in itself a form of implicit practice.

More specifically, we are arguing for an expanded view of the interpretation of the improvement that can result from taking tests multiple times. Traditionally, this "retesting effect" is often seen as uninteresting, involving low-level effects such as learning which key to press for a particular response. However, we suggest that in this case something more interesting was taking place; we think that taking multiple, distinct tests at different times distributed throughout the experiment may have led the participants to think more about relevant spatial information and to do better than they would if they simply took a single test twice. Comparing and contrasting across different kinds of tests may help participants think about the similarities and differences among the tests and therefore focus on improving spatial thinking more than they otherwise would (see Bransford & Schwartz, 1999; Gentner & Markman, 1997).

Further support for the claim that multiple testing can be an important source of spatially relevant practice comes from an analysis of the *kinds* of tasks that control groups performed. Across the literature, **(p. 879)** there was substantial variation in the "filler" tasks that control groups completed while the experimental groups were practicing the relevant spatial skills. In many cases, researchers deliberately used nonspatial filler tasks, such as playing Solitaire or taking vocabulary tests. In other cases, however, the researchers had the control group perform spatial filler tasks that differed from the experimental task in some specific way. For example, Feng, Spence, and Pratt (2007) were specifically interested in the effects of practicing *action* video games on the mental transformation of three-dimensional (3D) shapes. Their control group therefore practiced a nonactive but 3D puzzle video game called *Ballance.*

We coded each control group's filler activity and compared the impact of spatial versus nonspatial fillers on a study's overall effect size. Studies in which the control group performed a spatial filler task had significantly lower effects sizes than studies in which the control group performed a nonspatial filler. This result suggests that control groups learned something from material that was not directly tested—from the filler tasks. Having a spatial filler task led to more improvement in the control group, which had the ironic effect of lowering the overall effect size. The difference between the experimental and control groups was lower because the control group improved so much. Thus, the filler tasks were a form of implicit practice; the participants were not aware they were learning something relevant to the outcome tests that they took, but nevertheless, experiencing the spatial filler tasks facilitated spatial learning.

A second reason to assume that something more interesting than simply practicing the response is going on is that the improvement in the control groups *transferred* to different tasks. That is, being in the *control* group led to better performance on the transfer items. Caution is needed in interpreting this finding because only a relatively small number of studies tested for transfer in the control group. Nonetheless, this result again provides evidence that some of the control-group activities provided real, although implicit, spatial practice. This implicit practice was sufficient both to promote the acquisition of skills and knowledge and the transfer of these skills to new tasks.

Sex

Males traditionally perform better than females on tasks involving the mental transformation of spatial information, particularly three-dimensional information (Halpern, 2012; Maccoby & Jacklin, 1974; Voyer, Voyer, & Bryden, 1995). Some researchers (e.g., Feng et al., 2007) have suggested that the sex difference can be reduced or even eliminated with training or practice. We found, however, that both sexes improved equally with practice. On average, males began at higher levels and maintained their advantage over the practice period. Of course, it is certainly possible that sex differences are declining with age, and that future meta-analyses may find smaller, or no, sex differences in spatial cognition (see Hyde & Linn, 2006).

Age

Generally speaking, the malleability of thinking declines with age, with children typically benefiting more from training, practice, or experience than adults do (although large effects can still be observed in adults). We did find that children improved more than adults did, but this result did not reach statistical significance. We believe a likely reason for the lack of a significant difference is that very few studies have included participants of substantially different ages. For example, a developmental psychologist might compare the performance of 5-year-olds and 7-year-olds, but he or she is unlikely to also include adolescents in the same study (although see Kail, 1986 for a notable exception). Likewise, it is very unusual to include young adolescents and adults in the same study. Thus, when assessing the effects of age on the magnitude of practice-related improvement, we must rely almost completely on comparisons across studies. Because different studies often vary in many ways, the variability of these cross-study age comparisons tends to be large, and hence it can be difficult to show that the differences between ages are greater than the variability within ages (see Hedges, Tipton, & Johnson, 2010a, 2010b; Uttal et al., 2012).

Understanding Mechanisms of Improvement

In this section we provide a more detailed, narrative review of two lines of research (practice on mental rotation and the effects of video game playing) to shed light on the *mechanisms* through which practice and training promote improvement in spatial tasks. This review is deliberately *not* comprehensive. Instead, we have chosen to focus on research that highlights the perceptual or cognitive mechanisms that improve with training or practice.

Mental Rotation

There has been a great deal of research on the cognitive mechanisms that support mental rotation, **(p. 880)** and a smaller but growing body of work on the effects of practice on mental rotation. In combination, these lines of work have allowed researchers to be very specific about how, when, and why practice leads to improvement in mental rotation.

In classic (e.g., Cooper, 1975; Shepard & Metzler, 1971) mental rotation tasks, participants are asked to judge whether a presented stimulus is a rotated or reflected (mirror) image of a target stimulus. If the stimulus is a rotated transformation of the target, then it can be reoriented (mentally or physically) to match the target. For example, if the stimulus has been rotated 90 degrees relative to the target, then it can be rotated –90 degrees to bring it into alignment with the target. In contrast, no amount of rotation can bring a reflected image into alignment with the target. Researchers typically measure both the accuracy of judgment and the time needed to make the judgments.

There is a strong, linear relation between the degree of angular disparity and reaction time; the more the stimulus is rotated relative to the target, the longer the judgment takes. The very strong, linear relation is often taken as evidence that participants mentally rotate the stimulus (Kosslyn, 1986; Shepard & Metzler, 1971), a claim that has been further supported by neuropsychological evidence (e.g., Kosslyn, 1996; Kosslyn et al., 1993).

Our focus is on whether, and how, practice affects the process of mental rotation. Practice can deliberately improve reaction time and can also improve the accuracy of responses. Addressing when, why, and how this happens turns out to shed light not only on the effects of practice but also on the fundamental mechanisms that support mental rotation.

Effects of Practice on Mental Rotation

Practice leads to substantial improvements in mental rotation response times (e.g., Kail, 1986; Tarr & Pinker, 1989; Widenbauer, Schmid, & Jasnson-Osmann, 2007). Why? Consider first one simple possibility: Maybe practice leads people to simply get faster at rotating the stimulus. However, this ostensibly simple explanation turns out not to be so simple. The process of making a judgment in a mental rotation task, in fact, consists of at least four distinct, serial processes: (1) encoding the stimuli, (2) attempting to transform the stimulus into alignment with the target, (3) comparing stimuli and target to decide whether they are the same, and (4) responding (Cooper & Shepard, 1973; Shepard and Metzler, 1971; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). Each of these components could respond to training or practice, and improvement in any one of them could lead to decreases in reaction time. For example, it is possible that training might facilitate the encoding of the stimuli and thus allow people to make the decision about rotation and reflection more quickly. Likewise, practice could support faster motor responses and thus overall decreases in reaction time. With multiple processes involved, overall response times might decrease, even if the rate of the actual mental reorientation did not change.

How can we determine which processes are influenced by practice? Decomposition of the function that relates the degree of misalignment and reaction time can provide important insights. Generally speaking, the slope of the line represents the speed of the transformation process (Shepard & Metzler, 1971; Wright et al., 2008). Steeper slopes indicate slower responses. Thus, if practice leads to increases in the speed of the transformation process, then slopes will become flatter with practice. In contrast, the level of the Y-intercept reflects overall processing speed and is not affected by the magnitude of the rotation of the stimulus. Changes in the Y-intercept of performance are thus thought to reflect processes other than the actual spatial transformation of the stimulus object or figure.

Several studies have used this decomposition method to assess when and how practice affects performance on mental rotation. For example, Wright et al. (2008) investigated the effect of intensive practice on two spatial tasks, mental rotation and mental paper folding, and a control task, making judgments about similarities in the meanings of pairs of words. Thirty-eight subjects were recruited from a Harvard psychology department Web site with a mean age of 24 years old. Participants first took all three tests to provide baseline measures. They were then assigned to practice either the mental rotation task or the mental paper-folding task. Participants completed 21 daily practice sessions, during which they received 114 trials of the assigned task. In each practice session, approximately half of the items were present in the initial testing, and approximately half were completely new. Each training session lasted about 15 to 20 minutes. After the training sessions, both groups then retook the same tests that they had taken initially.

Practice led to substantial improvements, particularly in reaction time. Participants improved on both the mental rotation and mental paper-folding (p. 881) tasks, regardless of which task they practiced, indicating transfer between the spatial tasks. As expected, there was no transfer to the nonspatial verbal task.

Decomposition of the functions relating reaction time to degree of rotation revealed that much of the effect of practice was on the Y-intercept, not the slope. This result suggests that the effect of practice on mental rotation is *not* on the actual spatial transformation (i.e., mental rotation per se) but rather on other elements of the task. This possibility is discussed in more detail later, as it also relates to a discussion of the influences of video game practice on spatial cognition.

These results should not be interpreted as indicating that practice can never affect the slope of the mental rotation function. There are some cases in which practice may lead to a novel approach to the task, and this difference may be reflected in a changing slope. A classic example comes form the work of Tarr and Pinker (1989). They asked participants to make spatial judgments about a set of letter-like figures that were presented in different orientations. At first, participants seemed to use the standard strategy of rotating each stimulus into alignment with the target; reaction time increased linearly with increases in the angle of rotation, and the slope of this function was similar to that of earlier studies (e.g., Shepard & Metzler, 1971). However, with practice, the slope of the function approached zero, indicating that participants' reaction time was not affected by the degree of rotation. Tarr and Pinker suggested that with practice, participants fundamentally altered how they performed the task. They recognized the figure shapes of the previously displayed orientations and hence could respond with prior knowledge instead of the time-consuming task of rotating the stimulus into orientation with the target. Importantly, this effect did not transfer to different orientations. When the stimuli were presented in orientations that differed from the practice stimuli, the reaction time was again highly correlated with the degree of rotation of the stimulus.

In summary, Tarr and Pinker's (1989) results show that practice can help people to recognize particular figures, but the facilitative effect of doing so is limited to those figures and orientations specifically practiced. The time required to make the judgments was not reduced because people rotated the stimuli more quickly but because practice made it possible to make the judgments without rotating the stimuli at all.

The Effects of Video Game Practice on Spatial Cognition

Playing video games is another activity that has been show to improve performance on a variety of spatially relevant tasks. Studies of this type have garnered a great deal of attention, in part because of the general interest in video games as contexts for learning. As Gee (2003) has noted, playing video games is fun and does not "feel" like learning, often motivating people to play for countless hours simply to master the challenges offered. Much of the focus on the cognitive benefits of video game playing has been in the area of spatial perception, attention, and cognition (e.g., Spence & Feng, 2010; Subrahmanyam & Greenfield, 1994, 2008). Reviewing this literature sheds substantial light not only on the influence of video game thinking on spatial reasoning but also on the basic mechanisms of spatial cognition.

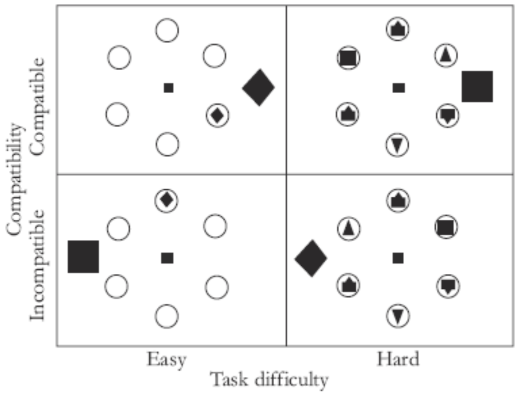

Figure 55.1 Example of the Flanker Compatibility Task (from Green & Bavelier, 2004).

In several cases, researchers have been very specific about how practice has its effects. For example, a series of studies by Green and Bavelier (2003, 2006a, 2006b, 2007) has shown that playing action video games can enhance both the capacity and resolution of visual-spatial attention. Green and Bevalier first compared experienced gamers' performance on a variety of classic tasks that assess the capacity of visual-spatial attention. One is the flanker compatibility task, which is illustrated in Figure 55.1. The participant's task is to decide whether a circle or a square appeared within the shapes that form the ring, while ignoring the large "flanker" stimulus that appears outside of the ring of circles. As the figure illustrates, sometimes the flanker was the same as the target (compatible trials) and sometimes it was the opposite of the target (incompatible trials). Typically, a compatible flanker improves (p. 882) performance in the easy version of the task, in which the participant needs to search in only one member of the ring to find the target. For most participants, the shape of the flanker has little effect on performance in the difficult version of the task because they cannot simultaneously attend to the flanker and search for the target among the many foils. However, Green and Bavalier found that video game players continue to benefit from a compatible flanker even on the difficult trials. This result suggests that playing video games expands the amount of information to which people can attend. Similar results were found for other tasks that measure the span or capacity of visual attention.

These results were very interesting, but the design of this first study did not allow for the assessment of cause and effect. Perhaps those individuals with exceptional visual-spatial attention are more likely to start playing video games in the first place, or at least more likely to "get hooked" and hence become serious gamers. To address this potential confound, Green and Bevalier conducted an additional experimental study with participants who said they seldom or never played video games. One-half of the participants were randomly assigned to practice video game playing. The remaining participants were assigned to a control group that performed a vocabulary task. Participants practiced for approximately 10 hours.

This experimental design allowed Green and Bevalier to assess whether video game playing *caused* the improvement in visual-spatial capacity. The answer was yes; participants assigned to the video game playing group improved significantly more on the tests of visual-spatial attentional capacity than the control group did. The effect of the 2-week intervention was not as strong as the effect of a lifetime of being a serious gamer, but nevertheless it was strong and statistically significant. This result suggests that practicing video games can cause an increase in visual-spatial attention capacity.

The research presented thus far establishes that playing video games can increase the capacity of visual-spatial attention. In subsequent work, Green and Bavelier (2007) also showed the playing video games can increase the *resolution* of the information in visual-spatial attention as well. This work tested the effect of video game playing on the *crowding* phenomenon. Individual objects become progressively more difficult to identify when they are presented in the same area as other objects than when presented apart from other objects. Each target has a c*rowding region*; the perception of an individual object also sets up a zone of inhibition that makes it more difficult to see surrounding objects. Green and Bavalier showed the crowding region is significantly *smaller* in video game players than in people who do not play video games. Thus, gamers experience *less* crowding and have greater attentional resolution, allowing them to see, identify, and keep track of the locations of more objects.

It is interesting to note that the effects of practice in this case are again largely or even completely implicit. Participants did not try to increase their visual-spatial capacity or resolution while playing video games. They probably were not aware it was happening. Nevertheless, it did happen, again showing that practice need not be deliberate to promote gains in performance that can also transfer to other tasks.

Extension of Video Game Practice to Other Spatial Tasks

The studies reviewed thus far demonstrate that playing video games can increase the capacity and resolution of visual-spatial attention capacity. Feng, Spence, and Pratt (2007) extended these results to include other spatial tasks, such as mental rotation. They found that practicing video games leads to substantial improvement in mental rotation, and moreover, that the advantage gets *larger* after a delay; participants performed *better* after a 2-week delay than they did immediately after the experiment. This result is very important because it suggests that the effect was not a fleeting boost that is directly tied to playing the game. Therefore, playing video games may lead to long-term improvement in visual-spatial tasks.

Explaining the Influences of Video Game Playing

Based on these results, Spence and Feng (2010) offered a general explanation for the effects of playing video games on performance for both video games and spatial cognition tasks. As already mentioned, the effects entail increases in both the capacity and acuity of visual attention. For example, greater visual-spatial attention capacity will allow a player to pick up on approaching “enemies” (and respond appropriately) sooner than someone with less visual-spatial attention capacity. Likewise, the ability to attend to what is happening on a wider portion of the screen will again give the experienced player more time to respond both to threats and opportunities to attack or otherwise score points. **(p. 883)** Skilled video game players can attend to a particular event on the screen (e.g., avoiding hitting an asteroid), while simultaneously monitoring what is happening in the periphery.

These skills transfer to other judgments that require actively attending to and making decisions regarding objects. The explanation for the improvement in tasks such as the flanker compatibility effect seem straightforward: If playing video games increases the capacity and resolution of spatial attention, then it will support performance in other tasks that also draw upon these cognitive resources. The far transfer to seemingly less related tasks, such as mental rotation, is particularly intriguing but can also be explained in terms of increases in attention, capacity, and acuity of visual-spatial attention. Mental rotation requires representing objects or figures and holding them in working memory as the transformation is made (e.g., Hyun & Luck, 2007; Miyake & Shah, 1999). Being able to attend to more information, and to hold it in working memory, could benefit the representation of individual figures substantially. For example, individuals with higher levels of spatial attention or working memory may be able to quickly form schematic representations of to-be-rotated figures and keep track of the elements of the figures during the transformation process (e.g., Just & Carpenter, 1985). They may have more time to abstract schematic representations of the to-be-rotated figures and use these schematic representations to facilitate the transformation (see Cooper, 1975). In summary, having greater attentional resources and resolution provides many potential benefits in the representation and recall of spatial figures and relations. This advantage may be domain general and thus may benefit performance in a wide variety of tasks (Spence & Feng, 2010).

Researchers (e.g., Green & Bavelier, 2008; Spence & Feng, 2010) have proposed a neurally motivated explanation for the improvements that practicing video games engenders. Central to the theory is the interaction between lower and higher level visual recognition processes. The visual (occipital) cortex first processes information about components of figures and passes this information on to higher (e.g., parietal and frontal) cortex, which then contribute to the analysis, recognition, and storing of spatial figures and relations. If the information is not sufficient to support the detection and discrimination of features, additional information must be retrieved from the visual cortex (see Ahissar & Hochstein, 2004). Spence and Feng suggested that playing action video games allows people to more often make judgments and discriminations about information in the higher cortical areas without having to refer back to the lower level information. This change decreases the average amount of time that it takes to make decisions but does not affect the time required to transform this information. This explanation thus is consistent with the observation (e.g., Wright et al., 2008) that training affects the Y-intercept of the reaction time and degree of rotation function but does not typically affect the slope of this function. Note also that this capacity increase is not tied to particular stimuli and thus could support transfer to unpracticed tasks.

In summary, research on the effects of video game training has shed light on the mechanisms that are likely implicated when spatial training or practice leads to faster responses. If the right conditions are met, the training can provide precisely the large, durable, and transferable improvements that we reported in our meta-analysis of the research on the effects of spatial training and practice.

Summary and Conclusions

Our review has revealed that spatial cognition is quite malleable and that some kinds of experiences can have lasting and important benefits. Prior studies that reached other conclusions may have been affected by the unexpected improvement in control groups or by the use of stimuli that could be easily memorized and thus did not support more domain-general improvements. Our discussion of the mental processes that are affected by mental rotation practice or playing video games both supports our conclusions and provides information about how and why these benefits are obtained.

Finding that spatial cognition can be improved may have important implications for other topics, such as research on methods to promote STEM achievement and attainment. For example, we have argued (e.g., Uttal & Cohen, 2012) that spatial training programs, in which people actively practice STEM-relevant spatial tasks, could help to prevent some of the substantial dropout that occurs in STEM majors. Even relatively small amounts of practice could help people cope with the spatial demands of tasks such as representing the structures of molecules or the forces that are acting on a bridge or other structure.

We end by asking whether the experiences of everyday life are sufficient to provide sufficient practice in spatial thinking. When we mention the possibility of including spatial training and practice as part of the STEM curriculum, we are (p. 884) sometimes asked why this is needed, since people use spatial cognition frequently in everyday tasks such as navigation. This question reveals a common assumption—reading and mathematics may take substantial amounts of practice, but spatial thinking does not. We strongly disagree with this assumption; everyday spatial experiences are almost certainly not sufficient to provide the kinds of practice that are needed to support STEM-related spatial thinking. Although everyone navigates, the cognitive skills that support navigation are only modestly related to those that support the processing of spatial figures and diagrams that is required in STEM (e.g., Allen, Kirasic, Dobson, Long, & Beck, 1996; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). Many kinds of spatial experiences do transfer to other tasks, but navigation does not appear to be one of them. In addition, the very high levels of improvement that are observed after only modest amounts of training suggest that people may enter these tasks with relatively low levels of spatial reasoning. Standard psychometric tests of spatial ability are normed to the population, but it is possible that these norms could be raised substantially with only moderate amounts of training.

In summary, our review of research indicates that spatial cognition is highly malleable, and that these effects both endure and transfer. Given the relatively little amount of time and money required to include spatial practice and training in school curricula, it is time to test whether interventions such as playing video games can improve STEM learning.

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Notes:

(1.) Several extreme outliers were removed from this, and all subsequent analyses.

(2.) *g* represents Hedges's *g*, the mean-weighted effect size and common metric for our meta-analyses. This statistic is a slightly more conservative version of Cohen's *d.*

David H. Uttal

David H. Uttal, Department of Psychology, Northwestern University, Evanston, IL

Nathaniel G. Meadow

Nathaniel G. Meadow, Department of Psychology, Northwestern University, Evanston, IL