# LEARNING VERSUS PERFORMANCE

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## LEARNING VERSUS PERFORMANCE

## INTRODUCTION

The major goal of instruction—whether in the classroom or in the field—is, or at least should be, to equip the learner with the type of knowledge or skills that are durable (i.e., capable of sustaining long periods of disuse) and flexible (i.e., capable of being applied in different contexts). That is, the goal of instruction is to facilitate *learning*, which must be inferred at some point *after* instruction. Learning, however, must be distinguished from *performance*, which is what can be observed and measured *during* instruction or training. This important and seemingly paradoxical distinction between learning and performance dates back decades, spurred by early research that revealed that learning can occur even when no discernible changes in performance are observed. For example, latent learning researchers demonstrated that rats could learn a maze during periods of free exploration in which their behavior was seemingly aimless (i.e., their performance was irregular). Similarly, findings in the overlearning literature suggested that considerable learning could occur well after performance during acquisition was at asymptote. In sum, this early research demonstrated that learning could occur without changes in performance. More recently, the converse has also been shown—specifically, that improvements in performance can fail to yield significant learning. In fact, numerous experiments in the domains of perceptual-motor learning and verbal-conceptual learning have shown certain manipulations—including distributing practice, varying the conditions of practice, reducing feedback, and testing/generation—to have opposite effects on learning and performance: Conditions that induce the most errors during acquisition are often the very conditions that lead to the most learning! Furthermore, that performance is often fleeting and, consequently, a highly imperfect index of learning does not appear to be appreciated by learners or instructors who frequently misinterpret short-term performance as a guide to long-term learning. These considerations, as well as others outlined in this article, suggest that the learning-performance distinction is critical and has implications abound, both practical and theoretical in nature.

## GENERAL OVERVIEWS

A number of reviews provide an introduction to the learning-versus-performance distinction and summarize key findings that illustrate the distinction. Schmidt and Lee 2011, for example, synthesizes theory and evidence from basic and applied research and offers readers a comprehensive discussion of the complex nature of the learning-versus-performance distinction in the context of motor skills. A couple reasons for this complexity, as noted in Lee and Genovese 1988, is that learning and performance are not always at odds and that researchers often diverge in their definitions of what constitutes learning and performance. Christina and Bjork 1991 and Wulf and Shea 2002 examine the impact—in terms of both learning and performance—of a number of variables that can be manipulated during skills training, and Lee 2012 and Schmidt and Bjork 1992 show that the distinction between learning and performance is as necessary and crucial in the verbal-learning domain as it is in the motor-learning domain. Finally, Bjork 1999 discusses how students and instructors alike often fail to appreciate the distinction between current performance and long-term learning, which makes them susceptible to mistaking the former as reliable index of the latter.

**Bjork, Robert A. 1999. Assessing your own competence: Heuristics and illusions. In *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application*. Edited by Daniel Gopher and Asher Koriat, 435–459. Cambridge, MA: MIT Press. [ISBN: 9780262090339][class:bookChapter]**

Reviews the evidence on which the distinction between learning and performance is based and focuses on the potential of learners to gain illusions of competence based on their interpreting good performance during the acquisition as evidence that learning, as measured by long-term retention and transfer, has been achieved.

**Christina, Robert W., and Robert A. Bjork. 1991. Optimizing long-term retention and transfer. In *In the mind's eye: Enhancing human performance*. Edited by Daniel Druckman and Robert A. Bjork, 23–56. Washington DC: National Academy Press. [ISBN: 9780309043984][class:bookChapter]**

Discusses the distinction between learning and performance, mostly in the context of motor learning, and provides a review of the training conditions that do and do not show differential influences on performance during training versus long-term retention and transfer.

**Lee, Timothy D. 2012. Contextual interference: Generalization and limitations. In *Skill acquisition in sport: Research, theory, and practice II*. Edited by Nicola J. Hodges and A. Mark Williams, 79–93. London: Routledge.[ISBN: 9780203133712] [class:bookChapter]**

This recent review discusses the contextual interference (CI) effect, a signature finding that supports the learning-performance distinction. Empirical evidence from both motor and verbal tasks is reviewed.

**Lee, Timothy D., and Elizabeth D. Genovese. 1988. Distributing of practice in motor skill acquisition: Learning and performance effects reconsidered. *Research Quarterly for Exercise and Sport* 59:277–287.[class:journalArticle]**

Highlights the importance of how learning and performance are defined and provides evidence that these two indices can be influenced in similar ways—in this case, a type of distributed practice was shown to increase short-term performance and long-term learning.

**Schmidt, Richard A., and Robert A. Bjork. 1992. New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science* 3:207–217. [doi:10.1111/j.1467-9280.1992.tb00029.x][class:journalArticle]**

Reviews evidence from the verbal and motor domains showing that short-term performance is an imperfect indicator of long-term retention and transfer, and in doing so, reveals common learning principles that underlie both verbal and motor learning.

**Schmidt, Richard A., and Timothy D. Lee. 2011. *Motor control and learning: A behavioral analysis.* 5th ed. Champaign, IL: Human Kinetics. [ISBN: 9780736079617][class:book]**

Provides a comprehensive analysis of the historical, theoretical, and empirical issues surrounding the complex nature of motor learning and performance.

**Wulf, Gabriele, and Charles H. Shea. 2002. Principles derived from the study of simple skills do not generalize to complex skill learning. *Psychonomic Bulletin and Review* 9:185–211. [doi:10.3758/BF03196276][class:journalArticle]**

Reviews empirical work from the motor domain and, in doing so, advises caution with respect to generalizing results from experiments using simple tasks to more complex skill learning.

**JOURNALS**

There are many peer-reviewed journals that publish articles—including empirical, review, and meta-analytic—relevant to the distinction between learning and performance. Furthermore, given that this distinction is made in both motor and non-motor domains, this topic spans a particularly diverse range of journals. The journals mentioned here are the primary outlets for research related to learning versus performance, but they certainly do not comprise an exhaustive list. **Journal of Motor Behavior** and **Perceptual and Motor Skills** publish on a diverse range of issues for those readers primarily interested in the learning and development of motor skills. **Journal of Experimental Psychology: Animal Behavior Processes**; **Journal of Experimental Psychology: General**; and **Journal of Experimental Psychology: Learning, Memory, and Cognition** are three journals published by the American Psychological Association (APA) that focus on basic and applied research that span the motor and verbal domains. **Memory and Cognition** is intended for a general readership interested in human cognition exclusively. **Psychonomic Bulletin and Review** attracts a broad audience by publishing work on a wide range of topics in experimental psychology, covering both human and non-human cognition. Finally, **Psychological Science** is the flagship journal of the Association for Psychological Science (APS), publishing articles that span the entire spectrum of psychological research.

***Journal of Experimental Psychology: Animal Behavior Processes [http://www.apa.org/pubs/journals/xan/index.aspx]*.[class:periodical]**

Published quarterly by the American Psychological Association (APA). As the name suggests, it publishes empirical and theoretical articles mostly on non-human animal research, although human research is also published by this journal.

***Journal of Experimental Psychology: General [http://www.apa.org/pubs/journals/xge/index.aspx]*.[class:periodical]**

This quarterly publication of the American Psychological Association (APA) publishes a wide range of articles in experimental psychology, particularly those that integrate ideas from two or more areas.

***Journal of Experimental Psychology: Learning, Memory, and Cognition [http://www.apa.org/pubs/journals/xlm/index.aspx]*.[class:periodical]**
Another journal published bi-monthly by the American Psychological Association (APA), it publishes empirical and review articles examining the basic cognitive processes underlying learning, memory, and decision making, among other topics.

***Journal of Motor Behavior [http://www.tandfonline.com/action/aboutThisJournal?show=aimsScope&journalCode=vjmb20]*.[class:periodical]**
Published bi-monthly by Taylor and Francis, this journal takes a multidisciplinary approach to understanding the basic processes underlying motor control. It publishes empirical and review articles.

***Memory and Cognition [http://www.springer.com/psychology/cognitive+psychology/journal/13421]*.[class:periodical]**
This journal is published approximately bi-monthly by Springer and is a publication of the Psychonomic Society. It covers a broad range of empirical work regarding human learning and memory.

***Perceptual and Motor Skills [http://www.amsciepub.com/loi/pms]*.[class:periodical]**
Published bi-monthly by Ammons Scientific, this journal primarily focuses on experimental and theoretical articles related to the impact of experience on motor skill learning.

***Psychological Science [http://www.psychologicalscience.org/index.php/publications/journals/psychological_science]*.[class:periodical]**
Published monthly, this is the flagship journal of the Association for Psychological Science (APS). It publishes empirical and review articles devoted to research, theory, and applications of work spanning the entire field of psychology.

***Psychonomic Bulletin and Review [http://www.springer.com/psychology/cognitive+psychology/journal/13423]*.[class:periodical]**

Published bi-monthly by Springer and a publication of the Psychonomic Society, it primarily publishes review articles and brief empirical reports. It is intended for a general readership, covering topics that span all areas of experimental psychology.

## FOUNDATIONAL STUDIES

Studies conducted decades ago necessitated the distinction between learning and performance by showing that considerable learning could occur in the absence of changes in performance. In the animal literature, latent learning researchers demonstrated that rats' learning of a maze could be enhanced by permitting a period of free exploration in which their behavior seemed aimless (i.e., performance was irregular). Likewise, research in overlearning found that additional learning/practice trials provided after performance was at asymptote and no longer changing resulted in slowed forgetting and more rapid relearning. Studies in which fatigue stalled, or even suppressed, performance on to-be-learned motor tasks also demonstrated that learning could continue in the absence of changes in performance. This section reviews these foundational studies.

### Latent Learning

Latent learning is defined as learning that occurs in the absence of any obvious reinforcement or noticeable behavioral changes. Learning is said to be "latent" because it is not exhibited unless a reinforcement of some kind is introduced to reveal it. Blodgett 1929 was the first to demonstrate such learning in non-human animals. In his experiment, hungry rats were first placed in a maze without being rewarded for reaching the goal box. Unsurprisingly, these rats failed to show marked improvement—as measured by errors—in reaching the goal. That is, their performance was stagnant during this exploration period. However, once food was introduced as a reward, their error rates immediately dropped to a level comparable to rats that were reinforcement from the outset. Thus, it was concluded that learning could occur without performance gains. The following year, in what is now considered a classic article, Tolman and Honzik 1930 replicated these findings. Reynolds 1945 and Seward 1949 later advanced ideas of latent learning by demonstrating that the amount of time spent in the maze with no reinforcement was positively related to rats learning the maze. Similarly, Bendig 1952 showed that the number of pre-exposures to the maze matters as well. Postman and Tuma 1954 and Stevenson 1954 are seminal studies that revealed latent learning in humans. Finally, for a classic review of early latent learning studies, Tolman 1948 is recommended, in which the concept of "cognitive maps" was introduced.

**Bendig, Albert W. 1952. Latent learning in a water maze. *Journal of Experimental Psychology* 43:134–137. [doi:10.1037/h0059428][class:journalArticle]**

Using a water maze, Bendig found that latent learning in rats increased with the amount of non-rewarded pre-exposures to the maze in which no changes in performance were discernible.

**Blodgett, Hugh C. 1929. The effect of the introduction of reward upon the maze performance of rats. *University of California Publications in Psychology* 4:113–134.[class:journalArticle]**

This was the first latent learning experiment. During free exploration of a maze in which no changes in performance were observed, rats nonetheless learned the maze as evidenced by their performance after reinforcement was introduced.

**Postman, Leo, and A. H. Tuma. 1954. Latent learning in human subject. *The American Journal of Psychology* 67:119–123. [doi:10.2307/1418076][class:journalArticle]**

Whereas most early experiments of latent learning were conducted with rats, this seminal article reports an experiment in which latent learning is demonstrated in humans learning a maze.

**Reynolds, Bradley. 1945. A repetition of the Blodgett experiment on "latent learning." *Journal of Experimental Psychology* 35:506–516. [doi:10.1037/h0060742][class:journalArticle]**

This experiment was the first to show that latent learning in rats could occur over relatively short time intervals—in this case, in a matter of a few days.

**Seward, John P. 1949. An experimental analysis of latent learning. *Journal of Experimental Psychology* 39:177–186. [doi:10.1037/h0063169][class:journalArticle]**

Compared to rats that were not permitted an exploration period in a maze, rats that were given just thirty minutes of free exploration showed greater learning of the maze after reward was introduced.

**Stevenson, Harold W. 1954. Latent learning in children. *Journal of Experimental Psychology* 47:17–21. [doi:10.1037/h0060086][class:journalArticle]**

Reports latent learning in children—some as young as three years old—as evidence by their learning of irrelevant, peripheral objects during a task in which a key was to be found to open a box.

**Tolman, Edward C. 1948. Cognitive maps in rats and men. *Psychological Review* 55:198–208. [http://dx.doi.org/10.1037/h0061626][class:journalArticle]**

In this early review of work on latent learning, Tolman coined the term "cognitive map," which refers to a mental representation of one's spatial environment.

**Tolman, Edward C., and Charles H. Honzik. 1930. Insight in rats. *University of California Publications in Psychology* 4:215–232.[class:journalArticle]**

This classic experiment replicated Blodgett 1929 using a more complex maze. Rats learned the maze despite showing what appeared to be aimless performance during training.

**Overlearning and Fatigue**

Overlearning refers to the continued practice on a task after some criterion of mastery on that task has been achieved. A pianist, for example, might continue to practice a piece despite already being able to perform it. Furthermore, the degree of overlearning can be expressed by the amount of post-mastery trials divided by the amount of trials needed to reach mastery. If the pianist practiced a piece five additional times after needing ten practice trials to master it, then the degree of overlearning would be 50 percent. Although the earliest work on overlearning can be traced to Ebbinghaus 1964 (originally published in 1885), Krueger 1929 represents the most frequently cited study on overlearning. In this experiment, participants who overlearned lists of words by 100 percent—meaning that they studied them twice as many times as needed to master them—showed greater retention on a long-term test than did participants who mastered—but did not overlearn—the list during the initial study phase. Krueger 1930 then showed that the retention increased with the amount of overlearning during practice, and Gilbert 1957 showed the same was true for more complex verbal learning materials. The occurrence of learning in the absence of performance gains has also been shown in the domain of motor skills. Adams and Reynolds 1954 and Stelmach 1969 showed that during trials in which fatigue hindered, or even suppressed, performance, learning nonetheless occurred. Citing these early studies, Fitts 1965 concluded that the "The importance of continuing practice beyond the point in time where some . . . criterion is reached cannot be overemphasized" (p. 195).

**Adams, Jack A., and Bradley Reynolds. 1954. Effect of shift in distribution of practice conditions following interpolated rest. *Journal of Experimental Psychology* 47:32–36. [doi:10.1037/h0061881][class:journalArticle]**

Learning on a rotary pursuit task continued to occur even across trials in which fatigue prevented any further gains in performance during training.

**Ebbinghaus, Hermann. 1964. *Memory: A contribution to experimental psychology*. Translated by H. A. Ruger, C. E. Bussenius, and E. R. Hilgard. New York: Dover.[class:book]**

This represents the earliest work examining overlearning. Using consonant-vowel-consonant "nonsense syllables," Ebbinghaus showed that overlearning material renders that material more resistant to forgetting.

**Fitts, Paul M. 1965. Factors in complex skill training. In *Training research and education*. Edited by Robert Galser, 177–197. New York: Wiley.[class:bookChapter]**

Provides a thorough review of the early experiments on overlearning, emphasizing the effectiveness and applications of this learning technique.

**Gilbert, Thomas F. 1957. Overlearning and the retention of meaningful prose. *Journal of General Psychology* 56:281–289. [doi:10.1080/00221309.1957.9920339][class:journalArticle]**

Using more complex verbal materials—in this case, prose passages—Gilbert showed that retention, or relearning, increases as a function of the degree of earlier overlearning.

**Krueger, W. C. F. 1929. The effect of overlearning on retention. *Journal of Experimental Psychology* 12:71–78. [doi:10.1037/h0072036][class:journalArticle]**

In this seminal study, words that were subject to 100 percent overlearning were better recalled after a retention interval than were lists that were mastered, but not overlearned.

**Krueger, W. C. F. 1930. Further studies in overlearning. *Journal of Experimental Psychology* 13:152–163. [doi:10.1037/h0075484][class:journalArticle]**

Using a maze tracing task, Krueger demonstrated that the amount of overlearning is positively related to retention. Specifically, a monotonic increase in retention was observed comparing conditions of 100 percent learning, 50 percent overlearning, and 100 percent overlearning.

**Stelmach, George E. 1969. Efficiency of motor learning as a function of intertrial rest. *The Research Quarterly* 40:198–202.[class:journalArticle]**

In this motor skills experiment, trials in which fatigue actually suppressed performance nonetheless resulted in substantial learning.

**Corresponding Conceptual Distinctions**

The dissociations between learning and performance observed in early experiments on latent learning and overlearning, plus other considerations, led major learning theorists (e.g., Estes 1955; Hull 1943; Skinner 1938) to distinguish between the “habit strength” of a response and the “momentary reaction potential” of that response, to use Hull’s terms; between “habit strength” and “response strength,” to use Estes’s terms; or between “reflex reserve” and “reflex strength,” to use Skinner’s terms. Empirically, habit strength, or reflex reserve (i.e., learning) was assumed to be indexed by resistance to extinction or forgetting—or by rapidity of relearning, whereas momentary reaction potential, response strength, or reflex strength (i.e., performance), was assumed to be indexed by the current probability, rate, or latency of a response. More recently, Bjork and Bjork 1992, in an effort to account for a range of findings in research on human verbal and motor learning, resurrected such a distinction as “storage strength” (i.e., learning) versus “retrieval strength” (i.e., performance). This account, as well as other current theoretical perspectives regarding the learning-performance distinction, is discussed under *Theoretical Perspectives*.

**Bjork, Robert A., and Elizabeth L. Bjork. 1992. A new theory of disuse and an old theory of stimulus fluctuation. In *From learning processes to cognitive processes: Essays in honor of William K. Estes.* Vol. 2. Edited by Alice F. Healy, Stephen M. Kosslyn, and Richard M. Shiffrin, 35–67. Hillsdale, NJ: Lawrence Erlbaum Associates. [ISBN: 9780805810974][class:bookChapter]**

In this chapter, a new theory of learning is formulated in which the old distinction between learning and performance is indexed by “storage strength” and “retrieval strength,” respectively.

**Estes, William K. 1955. Statistical theory of distributional phenomena in learning. *Psychological Review* 62:369–377. [doi:10.1037/h0046888][class:journalArticle]**

Estes developed a mathematical model of learning, called the fluctuation model, contained in which was the distinction between “habit strength” (learning) and “response strength” (performance).

**Hull, C. L. 1943. *Principles of behavior*. New York: Appleton-Century-Crofts.[class:book]**

In this book, Hull put forth a general theory of learning that distinguished between “habit strength” (learning) and “momentary reaction potential” (performance).

**Skinner, Burrhus F. 1938. *The behavior of organisms*. New York: Appleton-Century Crofts.[class:book]**

In his first published book, Skinner advanced the theory of operant conditioning and, in doing so, made the distinction between reflex reserve (learning) and reflex strength (performance).

## DISTRIBUTION OF PRACTICE

The early experiments on latent learning and overlearning suggested that learning can occur with no discernible changes in performance. More recently, the converse has also been demonstrated—namely, that performance gains during training can impede post-training learning compared to those conditions that induce more errors during performance. This dissociation has been demonstrated by manipulating the practice or study schedules of to-be-learned skills or information. Briefly, massing practice or study sessions—that is, practicing or studying the same thing over and over again—usually benefits short-term performance, whereas distributing practice or study—that is, separating practice or study sessions with time or other activities—usually facilities long-term learning of that skill or information. This section presents studies from both the motor and verbal domains in which the distribution of practice had differential influences on learning and performance.

### Motor-Learning Experiments

Suppose a swimmer wishes to improve his or her front, back, and butterfly strokes. Suppose further that the swimmer's training is restricted to one hour per day. One training option would be to mass (or block) the different strokes by practicing each for twenty minutes before moving on the next, never returning to the previously practiced strokes during that training session. Alternatively, she might distribute (or randomize) her practice schedule such that each stroke is practiced for ten minutes before moving on to the next stroke. This schedule would allow for each stroke to be revisited one more time during the training session. Research suggests that, whereas massing practice might promote rapid performance gains during training, distributing practice facilitates long-term retention of that skill. We note, however, that one complication is that a distributed-massed condition—that is, inserting time intervals between practice trials of the same skill—can, under some circumstances, boost short-term performance and long-term learning compared to a massed-massed condition, in which the skill is practiced over and over without inserting time between practice trials (see Lee and Genovese 1988, cited under *General Overviews*). Shea and Morgan 1979 and Simon and Bjork 2001, for example, showed this to be the case in controlled laboratory experiments on simple motor tasks. Similar findings have come from field-based studies examining more complex motor skills, including the learning of keyboard skills (Baddeley and Longman 1978), badminton serves (Goode and Magill 1986), and baseball swings (Hall, et al. 1994). Moreover, the benefits of distributed practice on learning have been showed in children (Ste-Marie, et al. 2004) and older adults (Lin, et al. 2010). Lee 2012 is recommended for a recent review regarding the influences of practice schedules on motor learning and performance.

**Baddeley, Alan D., and D. J. A. Longman. 1978. The influence of length and frequency of training session on the rate of learning to type.** ***Ergonomics*** **21:627–635. [doi:10.1080/00140137808931764][class:journalArticle]**

In a study conducted for the British Postal Service, distributed practice was more effective for learning typewriter keystrokes than massed practice; however, the opposite was true in regard to learning efficiency—that is, the distributed group required more days to reach any given level of performance relative to the massed group.

**Goode, Stephen, and Richard A. Magill. 1986. The contextual interference effects in learning three badminton serves.** ***Research Quarterly for Exercise and Sport*** **57:308–314.[class:journalArticle]**

Badminton players learned three different types of serves from one side of the court under blocked or randomly interleaved practice schedules. The blocked group performed better during training, whereas the interleaved group showed better retention and transfer (when tested on the opposite side of the court).

**Hall, Kellie G., Derek A. Domingues, and Richard Cavazos. 1994. Contextual interference effects with skilled baseball players.** ***Perceptual and Motor Skills*** **78:835–841. [doi:http://dx.doi.org/10.2466/pms.1994.78.3.835][class:journalArticle]**

During batting practice, baseball players received three different types of pitches that were either blocked by type of pitch or interleaved randomly. The blocked group had more solid hits during practice, but the interleaved group had more solid hits on a later retention test, even when that test was under blocked conditions.

**Lee, Timothy D. 2012. Contextual interference: Generalization and limitations. In** ***Skill acquisition in sport: Research, theory, and practice II*****. Edited by Nicola J. Hodges and A. Mark Williams, 79–93. London: Routledge.[ISBN: 9780203133712] [class:bookChapter]**

Surveys the literature regarding the effects of practice schedules on learning and performance and, in doing so, discusses the practical and theoretical implications of such work.

**Lin, Chien-Ho Janice, Allan D. Wu, Parima Udompholkul, and Barbara J. Knowlton. 2010. Contextual interference effects in sequence learning for younger and older adults.** ***Psychology and Aging*** **25:929–939. [doi:10.1037/a0020196][class:journalArticle]**

Similar to younger adults, this article demonstrates that older adults' long-term learning of a simple motor skill benefits from distributed practice.

**Shea, John B., and Robyn L. Morgan. 1979. Contextual interference effects on the acquisition, retention, and transfer of a motor skill.** ***Journal of Experimental Psychology: Human Learning and Memory*** **5:179–187. [doi:10.1037/0278-7393.5.2.179][class:journalArticle]**

Spurring hundreds of follow-up studies, this seminal article reported a laboratory-based motor skills experiment in which blocking practice on a given to-be-learning movement pattern facilitated acquisition performance, whereas interleaving practice on the several to-be-learned patterns facilitated learning, as measured by long-term retention and transfer.

**Simon, Dominic A., and Robert A. Bjork. 2001. Metacognition in motor learning.** ***Journal of Experimental Psychology: Learning, Memory, and Cognition*** **27:907–912. [doi:10.1037/0278-7393.27.4.907][class:journalArticle]**

Blocking practice on each of several to-be-learned keystroke patterns enhanced performance during training, relative to interleaved practice: but this led to poorer learning, as measured by the delayed test, whereas participants receiving blocked practice predicted they would perform better at a delay than did participants receiving interleaved practice.

**Ste-Marie, Diane M., Shannon E. Clark, Leanne C. Findlay, and Amy E. Latimer. 2004. High levels of contextual interference enhance handwriting acquisition.** ***Journal of Motor Behavior*** **36:115–126. [doi:10.3200/JMBR.36.1.115-126]**

In this study of the learning of handwriting skills, children learned best when practicing each letter distributed among other letters rather than practicing letter by letter.

**Verbal-Learning Experiments**

As in the motor domain, empirical evidence from verbal tasks suggests that distributing (or spacing) study opportunities benefits learning relative to massing them, a finding in the verbal literature termed the "spacing effect." Melton 1967, a classic article addressing the paradoxical nature of the spacing effect, notes that people are less likely to identify spaced items as being repetitions during the study session (i.e., a spacing-related decrement) but that these are the very items likely to be remembered on a later test. Since then, hundreds of experiments have demonstrated the spacing effect (for a review, see Cepeda, et al. 2006). The majority of these studies have focused on basic memory phenomena; however, spacing also improves the learning of logic (Carlson and Yaure 1990) and math (Taylor and Rohrer 2010), as well as inductive reasoning (Kornell and Bjork 2008). Finally, spacing effects are not limited to young adults, as learning in children (Taylor and Rohrer 2010) and older adults (Kornell, et al. 2010) benefit from such a study schedule. In this summary, we have grouped together situations in which spacing is achieved in two different ways: (a) by inserting periods of rest or unrelated activity between repetitions of to-be-learned information or procedures; and (b) by interleaving the learning trials on several different—and possibly interfering—to-be-learned tasks or verbal materials. A current active issue, however, is whether the benefits of interleaving go beyond the benefits of the spacing such interleaving introduces. Research in Kang and Pashler 2012 on the learning of artist's styles from examples of their paintings suggests that the benefits of interleaving come more from the opportunities interleaving provides for "discriminative contrasts" between the paintings of different artists than from spacing, per se. Birnbaum, et al. 2013, using pictures of birds and butterflies, found additional support for the idea that interleaving fosters inductive learning by juxtaposing exemplars of different to-be-learning categories; but this study also found that spacing can add to such benefits, provided it does not impede discriminative processing.

**Birnbaum Monica S., Nate Kornell, Elizabeth L. Bjork, and Robert A. Bjork. 2013. Why interleaving enhances inductive learning: The roles of discrimination and retrieval. *Memory and Cognition* 41:392–402. [doi:10.3758/s13421-012-0272-7][class:journalArticle]**

Using photographs of butterflies and birds, this study finds that temporal spacing harmed inductive learning when it interrupted the juxtaposition of exemplars from different categories that interleaving provides but that temporal spacing also has value when it does not interrupt discriminative processing.

**Carlson, Richard A., and Robin G. Yaure. 1990. Practice schedules and the use of component skills in problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 16:484–496. [doi:10.1037/0278-7393.16.3.484][class:journalArticle]**

Demonstrated that spacing benefits can be observed in the learning of Boolean logic.

**Cepeda, Nicholas J., Harold Pashler, Edward Vul, John T. Wixted, and Doug Rohrer. 2006. Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin* 132:354–380. [doi:10.1037/0033-2909.132.3.354][class:journalArticle]**

In reviewing the memory literature, this article showed that the spacing effect is highly robust and reliable.

**Kang, Sean H. K., and Harold Pashler. 2012. Learning painting styles: Spacing is advantageous when it promotes discriminative contrast. *Applied Cognitive Psychology* 26.1: 97–103. [doi:10.1002/acp.1801][class:journalArticle]**

Obtained results supporting the idea that mixing exemplars from different categories fosters inductive learning by highlighting differences between categories, whereas temporal spacing of exemplars per se does not support such induction.

**Kornell, Nate, and Robert A. Bjork. 2008. Learning concepts and categories: Is spacing the "enemy of induction?" *Psychological Science* 19:585–592. [doi:10.1111/j.1467-9280.2008.02127.x][class:journalArticle]**

Inductive learning—as measured by matching artists' names with never-before-seen paintings—benefited from previously studying these artists' paintings in a spaced fashion relative to massing them.

**Kornell, Nate, Alan D. Castel, Teal S. Eich, and Robert A. Bjork. 2010. Spacing as the friend of both memory and induction in younger and older adults. *Psychology and Aging* 25:498–503. [doi:10.1037/a0017807][class:journalArticle]**

In this study, spacing enhanced memory and inductive learning of artists' paintings in younger and older adults.

**Melton, Arthur W. 1967. Repetition and retrieval from memory. *Science* 158:532.[class:journalArticle]**

In this classic paper, Melton describes the spacing effect as paradoxical because it leads to decrements in short-term performance but enhancements in long-term learning.

**Taylor, Kelli, and Doug Rohrer. 2010. The effects of interleaved practice. *Applied Cognitive Psychology* 24:837–848. [doi:10.1002/acp.1598][class:journalArticle]**

Demonstrated that spacing various types of math problems helps children to solve novel problems—that is, spacing leads to better transfer than massing.

## VARIABILITY OF PRACTICE

Similar to distributing practice, varying the conditions of practice or study sessions—for example, by having a trainee practice skills related to, but different from, the target skill—can also have detrimental effects on performance during acquisition but can foster long-term learning and transfer. Most of the research in this vein has focused on motor learning, although a handful of studies on verbal learning have also demonstrated the long-term benefits of practice variability.

### Motor-Learning Experiments

Research on motor learning and practice variability suggests that if a basketball player, for example, wants to shoot accurate free throws, he or she should not only practice from the foul line itself but also from various positions neighboring the foul line. Such variable practice would not appear to be effective during practice—specifically, more errors would be induced relative to shooting only from the foul line—but would facilitate long-term learning. According to Schmidt 1975 and its schema theory of motor control, variable practice is effective because it enables one to become familiar with the general motor program underlying some skill (e.g., shooting a basketball). In terms of laboratory-based tasks, McCracken and Stelmach 1977 and Catalano and Kleiner 1984 show variable practice to be beneficial in learning simple timing tasks; Shea and Kohl 1991 demonstrates its effectiveness in learning specific grip strengths. With regard to more complex motor-skill learning, variable practice fosters learning to throw beanbags at a target (Kerr and Booth 1978), shooting the basketball (Landin, et al. 1993), and mastering racket skills (Green, et al. 1995). For a relatively recent review of variable practice effects on motor learning, Guadagnoli and Lee 2004 is recommended.

**Catalano, John F., and Brian M. Kleiner. 1984. Distant transfer in coincident timing as a function of variability of practice. *Perceptual and Motor Skills* 58:851–856.[class:journalArticle]**

Accuracy in reacting to the speed of a new object was enhanced for participants who were exposed the objects of various speeds (variable group) as opposed to only one speed (constant group).

**Green, Penelope D., Jean Whitehead, and David A. Sugden. 1995. Practice variability and transfer of a racket skill. *Perceptual and Motor Skills* 81:1275–1281. [doi:10.2466/pms.1995.81.3f.1275][class:journalArticle]**

In this study, variable practice benefited children learning a forehand racket skill.

**Guadagnoli, Mark A., and Timothy D. Lee. 2004. Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior* 36:212–224. [doi:10.3200/JMBR.36.2.212-224][class:journalArticle]**

Focuses on the effects of variable practice on motor learning, highlighting the generalities and limitations of such effects.

**Kerr, Robert, and Bernard Booth. 1978. Specific and varied practice of motor skill. *Perceptual and Motor Skills* 46:395–401.[class:journalArticle]**

Children tossed beanbags at a target from distances of two and four feet (variable group) or only three feet (constant group). On a later test distance of three feet—the sole distance practiced by the constant group—the variable group performance best.

**Landin, Dennis K., Edward P. Hebert, and M. Fairweather. 1993. The effects of variable practice on the performance of a basketball skill. *Research Quarterly for Exercise and Sport* 64:232–237.[class:journalArticle]**

In this study, basketball shooting was enhanced by variable practice (i.e., shooting from different locations) as opposed to shooting from only one location.

**McCracken, Hugh D., and George E. Stelmach. 1977. A test of the schema theory of discrete motor learning. *Journal of Motor Behavior* 9:193–201.[class:journalArticle]**

Participants were to knock over a barrier with their arm in 200 milliseconds from a given starting point. Those who practiced at various starting points performed worse than a constant-position group during acquisition but performed better when a new starting point was tested.

**Schmidt, Richard A. 1975. A schema theory of discrete motor skill learning. *Psychological Review* 82:225–260. [doi:10.1037/h0076770][class:journalArticle]**

Here a schema theory is advanced to explain the benefits of variable practice on motor learning. Variable practice, it is argued, fosters long-term learning because it helps one become familiar with the general motor program underlying a skill.

**Shea, Charles H., and Robert M. Kohl. 1991. Composition of practice: Influence on the retention of motor skills. *Research Quarterly for Exercise and Sport* 62:187–195.[class:journalArticle]**

Participants attempted to learn a criterion handgrip force. Compared to those who practiced solely to reach the criterion force, those who practiced additional handgrip forces performed worse during acquisition but better after a delay.

**Verbal-Learning Experiments**

Analogous to those findings in the motor domain, variable practice can also benefit verbal learning. Smith, et al. 1978 and Smith and Rothkopf 1984 show that varying the environmental context in which to-be-remembered material was presented increased the likelihood that the material would be recalled in a novel context. Mannes and Kintsch 1987 finds that providing outlines organized differently from a studied text passage promoted a deeper understanding of that passage compared to when the outline was organized similarly to the passage. Furthermore, increasing the variation of problems during an acquisition phase enhances analogical reasoning (Gick and Holyoak 1983), geometrical problem-solving (Paas and Van Merrienboer 1994), and complex troubleshooting (Van Merrienboer and de Croock 1997) of novel problems, as well as one's ability to solve previously encountered anagrams (Goode, et al. 2008).

**Gick, Mary L., and Keith J. Holyoak. 1983. Schema induction and analogical transfer. *Cognitive Psychology* 15:1–38. [doi:10.1016/0010-0285(83)90002-6][class:journalArticle]**

Showed that analogical transfer—in this case, solving novel problems by applying previously learned analogical rules—is facilitated by increasing the variation of preexposed analogy source problems.

**Goode, Michael K., Lisa Geraci, and Henry L. Roediger. 2008. Superiority of variable to repeated practice in transfer on anagram solution. *Psychonomic Bulletin and Review* 15:662–666. [doi:10.3758/PBR.15.3.662][class:journalArticle]**

Participants practiced solving anagrams by either solving multiple versions of the anagram that was tested later (variable practice group) or repeatedly solving the same version of those anagrams. Those who received variable practice solved more of the anagrams on a later test.

**Mannes, Suzanne M., and Walter Kintsch. 1987. Knowledge organization and text organization. *Cognition and Instruction* 4:91–115. [doi:10.1207/s1532690xci0402_2][class:journalArticle]**

Participants were given an outline that was organized either similarly or differently from a subsequently presented text passage. The former condition performed better on verbatim recall

of the passage; however, the latter condition was better at solving new problems that required a deeper understanding of the text material.

**Paas, Fred G. W. C., and Jeroen J. G. Van Merrienboer. 1994. Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive-load approach. *Journal of Educational Psychology* 86:122–133. [doi:10.1037/0022-0663.86.1.122]**

Showed that increasing the variation of worked geometrical problems increases the likelihood that novel geometrical problems will be successfully solved.

**Smith, Steven M., and Ernst Z. Rothkopf. 1984. Contextual enrichment and distribution of practice in the classroom. *Cognition and Instruction* 1:341–358. [doi:10.1207/s1532690xci0103_4][class:journalArticle]**

Four successive lectures with given in either the same location or in four different locations. The retention of key concepts from the lectures after one week was enhanced in the variable condition.

**Smith, Steven M., Arthur Glenberg, and Robert A. Bjork. 1978. Environmental context and human memory. *Memory and Cognition* 6:342–353. [doi:10.3758/BF03197465][class:journalArticle]**

In this study, varying the environmental context—in this case, rooms—across study sessions of word lists improved later recall in a novel setting.

**Van Merrienboer, Jeroen J. G., and Marcel B. M. de Croock. 1997. The transfer paradox: Effects of contextual interference on retention and transfer performance of a complex cognitive skill. *Perceptual and Motor Skills* 84:784–786. [doi:10.2466/pms.1997.84.3.784][class:journalArticle]**

The effects of variable practice on a complex troubleshooting task were investigated. Those who attempted highly variable practice problems made more errors during learning compared to a low-variability group, but showed better learning as evidence from new problems.

## AUGMENTED FEEDBACK

One common assumption has been that providing feedback from an external source (i.e., augmented feedback) during an acquisition phase fosters long-term learning to the extent that that feedback is given immediately, accurately, and frequently. However, a number of studies in the motor and verbal domains have challenged this assumption. Empirical evidence suggests that delaying, reducing, and summarizing feedback can be better for long-term learning than providing immediate, trial-by-trial feedback. However, the very feedback schedules that facilitate learning can have negligible (or even detrimental) performance effects during the acquisition phase. This section provides references from both the motor- and verbal-learning literatures that delve into this issue.

### Motor-Learning Experiments

Numerous motor learning studies—some of them dating back decades—have shown that frequent and immediate feedback can, contrary to intuition, degrade learning. Lavery 1962, a seminal article on simple motor learning, showed that providing feedback after every trial boosted performance during acquisition but obstructed later learning, compared to providing feedback after sets of trials in summary form. These effects were replicated in a frequently cited study by Schmidt, et al. 1989 in which specific arm movements were trained. Similarly, Vander Linden, et al.1993 and Schmidt and Wulf 1997 demonstrated that if feedback is given after each trial, it is best to delay that feedback—if even by a few seconds—for long-term retention to be supported. Finally, Winstein and Schmidt 1990 and Weeks and Kordus 1998 found that reducing the frequency of feedback conveyed during training boosts learning (but not short-term performance) of a simple arm movement and a complex soccer skill, respectively. Such findings are generally consistent with what Salmoni, et al. 1984 termed the guidance hypothesis, which proposes that feedback that is given too immediately and too frequently can lead learners to overly depend on it as an aid during practice, a reliance that is no longer afforded during later assessments of long-term learning when feedback is removed. For a review of feedback effects on motor learning and performance, Schmidt 1991 is recommended.

**Lavery, J. J. 1962. Retention of simple motor skills as a function of type of knowledge of results. *Canadian Journal of Psychology* 16:300–311. [doi:10.1037/h0083257][class:journalArticle]**

Reports that providing feedback in summary form (i.e., after a set of twenty trials) for a simple motor task resulted in poorer performance during acquisition, but better learning after a delay, than did providing feedback after each trial.

**Salmoni, Alan W., Richard A. Schmidt, and Charles B. Walter. 1984. Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin* 95:355–386. [doi:10.1037/0033-2909.95.3.355][class:journalArticle]**

The guidance hypothesis of feedback effects on motor learning is put forth in this widely cited article. According this hypothesis, frequent concurrent feedback can be detrimental to learning—but beneficial during acquisition—because it provides a crutch during practice that is no longer present during a later retention test.

**Schmidt, Richard A. 1991. Frequent augmented feedback can degrade learning: Evidence and interpretations. In *Tutorials in motor neuroscience*. Edited by J. Requin and G. E. Stelmach, 59–75. Dordrecht, The Netherlands: Kluwer. [ISBN: 9780792313854][class:bookChapter]**

Reviews the effects of various types of feedback on motor learning and performance.

**Schmidt, Richard A., and Gabriele Wulf. 1997. Continuous concurrent feedback degrades skill learning: Implications for training and simulation. *Human Factors* 39:509–525. [doi:10.1518/001872097778667979][class:journalArticle]**

This experiment showed that concurrent feedback on a discrete movement task boosts performance but hinders long-term learning, compared to delaying feedback just a few seconds.

**Schmidt, Richard A., Douglas E. Young, Stephan Swinnen, and Diane C. Shapiro. 1989. Summary knowledge of results for skill acquisition: Support for the guidance hypothesis. *Journal of Experimental Psychology: Leaning, Memory, and Cognition* 15:352–359. [doi:10.1037/0278-7393.15.2.352][class:journalArticle]**

In this study, participants were to learn specific arm movements. Feedback after every trial was better for acquisition during training (evidenced by fewer errors); but summary feedback, which occurred after multiple trials were completed, was better for long-term retention.

**Vander Linden, Darl W., James H. Cauraugh, and Tracy A. Greene. 1993. The effects of frequency of kinetic feedback on learning an isometric force production task in nondisabled subjects. *Physical Therapy* 73:79–87.[class:journalArticle]**

Training participants on an elbow-extension task, this study showed that delaying feedback until after the task was completed yielded greater long-term learning than concurrent feedback. Performance gains during acquisition, however, were made more rapidly by those receiving concurrent feedback.

**Weeks, Douglas L., and R. N. Kordus. 1998. Relative frequency of knowledge of performance and motor skill learning. *Research Quarterly for Exercise and Sport* 69:224–230.[class:journalArticle]**

The learning of soccer ball throw-ins by eleven- to fourteen-year-olds was enhanced by reducing the frequency of feedback during acquisition.

**Winstein, Carolee J., and Richard A. Schmidt. 1990. Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 16:677–691. [doi:10.1037/0278-7393.16.4.677][class:journalArticle]**

Reducing feedback to 50 percent of trials of was more beneficial for learning an arm-movement task compared to receiving feedback after 100 percent of trials; performance during acquisition showed the opposite effect.

### Verbal-Learning Experiments

In the motor domain, there is convincing evidence that withholding or delaying feedback, while potentially detrimental to performance during training, can facilitate long-term retention. Whether this is also true for verbal learning is more debatable. Thus, while we acknowledge that this remains a controversial issue in the verbal literature, we nonetheless find it appropriate to consider those experiments on verbal learning whose results are roughly analogous to those on motor learning. Schooler and Anderson 1990 demonstrates that reducing the frequency of feedback can impair performance during acquisition (but enhance long-term retention) of a computer language (LISP). Similarly, Hays, et al. 2010 finds that skipping feedback can enhance learning when the total time during the acquisition phase is fixed, and Pashler, et al. 2005 shows that providing feedback after correct responses made little difference for later learning. The timing of feedback has also been investigated. Kulhavy and Anderson 1972 reports that temporarily delaying corrective feedback to multiple choice questions enhanced learning compared to immediate feedback. The explanation was that the delay period allows one to forget incorrect answers, thereby reducing interference effects once corrective feedback is presented. This delayed-feedback effect has been subsequently replicated for learning prose passages (Butler, et al. 2007), geographical representations (Guzman-Munoz and Johnson 2007) and vocabulary in children (Metcalfe, et al. 2009). Importantly, these benefits persist even though delayed feedback may result in more laborious acquisition than immediate feedback. For a general review of the impact of feedback on learning in the laboratory and classroom, Hattie and Timperley 2007 is recommended.

**Butler, Anderw C., Jeffrey D. Karpicke, and Henry L. Roediger. 2007. The effect of type and timing of feedback on learning from multiple-choice tests.** ***Journal of Experimental Psychology: Applied*** **13:273–281. [doi:10.1037/1076-898X.13.4.273][class:journalArticle]**

After reading prose passages, participants took multiple-choice tests on those passages, receiving either immediate or delayed feedback after each answer. Delayed feedback led to better retention on final cued-recall test than did immediate feedback.

**Guzman-Munoz, Francisco J., and Addie Johnson. 2007. Error feedback and the acquisition of geographical representations.** ***Applied Cognitive Psychology*** **22:979–995. [doi:10.1002/acp.1410][class:journalArticle]**

An investigation of memory for geographical representations, this study showed that delayed feedback resulted in more arduous acquisition, but better long-term retention, than immediate feedback.

**Hattie, John, and Helen Timperley. 2007. The power of feedback. *Review of Educational Research* 77:81–112. [doi:10.3102/003465430298487][class:journalArticle]**

Provides a comprehensive review of the literature on the impact of feedback on learning, particularly in the classroom.

**Hays, Matthew J., Nate Kornell, and Robert A. Bjork. 2010. The costs and benefits of providing feedback during learning. *Psychonomic Bulletin and Review* 17:797–801. [doi:10.3758/PBR.17.6.797][class:journalArticle]**

Examines the effectiveness of feedback during a fixed-time acquisition phase. If permitted to skip feedback for correct answers, participants' learning was enhanced because more time could then be allocated to learning initially incorrect items.

**Kulhavy, Raymond W., and Richard C. Anderson. 1972. Delay-retention effect with multiple-choice tests. *Journal of Educational Psychology* 63:505–512. [doi:10.1037/h0033243][class:journalArticle]**

This frequently cited study showed that delayed feedback of incorrect answers led to superior learning on multiple choice tests compared to immediate feedback.

**Metcalfe, Janet, Nate Kornell, and Bridgid Finn. 2009. Delayed versus immediate feedback in children's and adults' vocabulary learning. *Memory and Cognition* 37:1077–1087. [doi:10.3758/MC.37.8.1077][class:journalArticle]**

In this study, the benefits of delayed versus immediate feedback in learning vocabulary were demonstrated in children. However, this benefit of delayed feedback did not occur in their adult sample.

**Pashler, Harold, Nicholas J. Cepeda, John T. Wixted, and Doug Rohrer. 2005. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31:3–8. [doi:10.1037/0278-7393.31.1.3][class:journalArticle]**

During an acquisition phase in which participants attempted to learn Luganda-English word translations, it was shown that feedback enhanced later learning only when given after incorrect answers; it had no learning benefit when provided after correct answers.

**Schooler, Lael J., and John R. Anderson. 1990. The disruptive potential of immediate feedback. In *Proceedings of the Cognitive Science Society*. Hillsdale, NJ: Lawrence Erlbaum Associates.[class:conference-proceeding]**

Examines the effects of feedback schedules in learning the computer language LISP. Decreasing the frequency of feedback obstructed performance during acquisition, but enhanced learning after a retention interval.

## TESTING AND GENERATION

Decades of research suggests that testing, or retrieval practice, changes the retrieved information in important ways. That is, tests not only act as passive assessments of what is stored in memory, as is often the traditional perspective in education, but also as vehicles that modify what is stored in memory. This section reviews evidence from both the motor- and verbal-learning domains that lead to such a conclusion. In the motor-skills literature, for example, to-be-learned movements that are self-produced are typically better learned than those that are externally guided or simply observed. Likewise, testing one's memory for verbal information, or having participants generate the information, enhances long-term retention of that material compared to reading it over and over, even in cases when corrective feedback is not provided. Critically, and relevant to the learning-performance distinction, the conditions that often facilitate long-term retention frequently induce more errors during acquisition than their counterpart conditions.

### Motor-Learning Experiments

When teaching a motor skill, such as a golf or tennis swing, it is commonplace for instructors to physically guide the learner through the desired motions. Intuition suggests that this type of instruction should be beneficial; indeed, research has shown than guiding learners reduces performance errors during acquisition compared to when learners attempt to produce the skill without guidance (i.e., are tested). The problem is that on assessments of long-term learning when guidance can no longer be relied upon, the reverse is often true—that is, those who practice a skill without guidance frequently show better learning than those who are guided during acquisition (for a recent review on guidance research, see Hodges and Campagnaro 2012). Such a dissociation between learning and performance was demonstrated decades ago by Baker 1968, which showed that guidance on a pursuit task minimized performance errors, but impeded long-term learning compared to an unguided group. Winstein, et al. 1994 and Feijen, et al. 2010 has replicated these guidance effects using different motor tasks. Similarly, Hagman 1983 shows that testing a skill after observing it once was better for later learning than was simply observing it multiple times. Finally, Stelmach, et al. 1975 is often credited for a convincing demonstration of a related phenomenon termed the “preselection effect,” which refers to the learning benefit that accompanies conditions where learners generate their own to-be-remembered movements as opposed to the movements being selected for them. For an early review on the preselection effect, Kelso and Wallace 1978 is recommended.

**Baker, C. H. 1968. An evaluation of guidance in learning a motor skill. *Canadian Journal of Psychology* 22:217–227. [doi:http://dx.doi.org/10.1037/h0082762][class:journalArticle]**

Participants were either guided or not guided during a joystick pursuit-tracking task. The guided group performed well during initial tests, but on a later retention test (six weeks later), this group demonstrated less learning than the unguided group and no better learning than a group who had never performed the task.

**Feijen, Lieke, Nicola J. Hodges, and Peter J. Beek. 2010. Acquiring a novel coordination skill without practicing the correct motor commands. *Journal of Motor Behavior* 42:295–306. [doi:10.1080/00222895.2010.504760][class:journalArticle]**

In a bimanual coordination task involving arm extensions, a guided group made fewer errors during the acquisition phase but showed less learning than groups who received either no guidance or partial guidance.

**Hagman, Joseph D. 1983. Presentation- and test-trial effects on acquisition and retention of distance and location. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 9:334–345. [doi:10.1037/0278-7393.9.2.334][class:journalArticle]**

In three experiments involving an arm-positioning task, Hagman found that multiple test trials in which participants repeated a once-presented position were more effective for long-term retention than were four presentation trials. The opposite was true for performance during acquisition.

**Hodges, Nicola J., and Paul Campagnaro. 2012. Physical guidance research: Assisting principles and supporting evidence. In *Skill acquisition in sport: Research, theory and practice.* 2d ed. Edited by Nicola J. Hodges and A. Mark Williams, 150–169. London: Routledge/Taylor and Francis. [ISBN: 9780415270748][class:bookChapter]**

Surveys the literature on guidance research in motor learning, providing evidence that, on the whole, passive guidance is less effective for learning than active involvement, despite the latter condition typically making more performance errors during acquisition.

**Kelso, J. A. S., and Stephen A. Wallace. 1978. Conscious mechanisms in movement. In *Information processing in motor control and learning*. Edited by George E. Stelmach, 79–116. New York: Academic Press. [ISBN: 9780126659603][class:bookChapter]**

Presents evidence that the preselection effect—that self-defined movements are more resistant to forgetting than experimenter-defined movements—is one of the most robust and reliable effects in the motor learning literature.

**Stelmach, George E., J. A. S. Kelso, and Stephen A. Wallace. 1975. Preselection in short-term motor memory. *Journal of Experimental Psychology: Human Learning and Memory* 1:745–755. [doi:10.1037/0278-7393.1.6.745][class:journalArticle]**

Participants were able to reproduce a rapid arm movement with much greater precision after a retention interval if that movement was selected by the participant rather than imposed by the experimenter.

**Winstein, Carolee J., Patricia S. Pohl, and Rebecca Lewthwaite. 1994. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Research Quarterly for Exercise and Sport* 70:316–323.[class:journalArticle]**

During a task in which a lever was manipulated to various positions, a physically guided group performed better during acquisition (i.e., made fewer errors) but worse after a retention interval than an unguided group.

**Verbal-Learning Experiments**

Similar to the motor-skills literature, empirical work investigating the effects of testing verbal material dates back decades, out of which has emerged the consensus that retrieving information from memory does more than reveal that the information exists in memory. In fact, the act of retrieval is a “memory modifier” (Bjork 1975) in the sense that it renders the retrieved information more recallable in the future than it would have been otherwise and can change that information considerably. For a comprehensive review of the testing effect on verbal learning, see Roediger and Karpicke 2006a. This section considers work that has contributed to the general notion that retrieval has positive impacts on learning, even when short-term performance is impeded by such retrieval. In one of the first demonstrations that testing can have differential effects on learning and performance, Hogan and Kintsch 1971 had participants study a word list either three times before being immediately tested on it (SSST) or once before being immediately tested on it three times in a row (STTT). During the fourth phase of this procedure in which both groups were tested, the SSST condition showed greater short-term recall performance than the STTT condition; however, no differences in long-term learning were evident on a free recall test administered one week later. Roediger and Karpicke 2006b demonstrates this general finding with more educationally relevant materials (prose passages), and Landauer and Bjork 1978 shows that an expanding retrieval schedule, in which the between-testing intervals increase over time, may be particularly effective for learning. Finally, research on a closely related phenomenon, the generation effect, also points to the benefits of retrieval. Slamecka and Graf 1978, for example, shows that having participants generate opposites when presented with a word (e.g., *hot-???*) was better for learning the second word than simply reading it (e.g., *hot-cold*). Kornell, et al. 2009 finds that the effectiveness of subsequent study opportunities can be potentiated even after generating information that is assured to be incorrect. For a recent meta-analysis on the power of the generation effect, Bertsch, et al. 2007 is recommended.

**Bertsch, Sharon, Bryan J. Pesta, Richard Wiscott, and Michael A. McDaniel. 2007. The generation effect: A meta-analytic review. *Memory and Cognition* 35:201–210. [doi:10.3758/BF03193441][class:journalArticle]**

This meta-analysis examined eighty-six studies (445 effect sizes) on the generation effect, which was shown to have a robust advantage over reading.

**Bjork, Robert A. 1975. Retrieval as a memory modifier. In *Information processing and cognition: The Loyola Symposium*. Edited by Robert Solso, 123–144. Hillsdale, NJ: Lawrence Erlbaum Associates. [ISBN: 9780470812303][class:bookChapter]**

Provides an early statement of the evidence and arguments supporting the now-accepted idea that retrieving information from memory alters the state of the system.

**Hogan, Robert M., and Walter Kintsch. 1971. Differential effects of study and test trials on long-term recognition and recall. *Journal of Verbal Learning and Verbal Behavior* 10:562–567. [doi:10.1016/S0022-5371(71)80029-4][class:journalArticle]**

Participants studied single words either three times before taking a test (SSST) or once before taking three tests (STTT). Short-term recall performance was better in the SSST condition; however, long-term recall did not differ between the two conditions. Interestingly, later recognition was best in the SSST condition.

**Kornell, Nate, Matthew J. Hays, and Robert A. Bjork. 2009. Unsuccessful retrieval attempts enhance subsequent learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 35:989–998. [doi:10.1037/a0015729][class:journalArticle]**

Demonstrates that generation during acquisition, even if errorful, can lead to learning benefits over reading provided corrective feedback is given immediately after generation. That is, generation can potential subsequent study opportunities.

**Landauer, Thomas K., and Robert A. Bjork. 1978. Optimum rehearsal patterns and name learning. In *Practical aspects of memory*. Edited by Michael M. Gruneberg, Peter E. Morris, and Robert N. Sykes, 625–632. London: Academic Press. [ISBN: 9780123050502][class:bookChapter]**

In paired-associate learning tasks, expanding-interval testing schedules produced better recall than equal-interval testing schedules. Moreover, both of these conditions trumped a massed-testing condition, in which tests were administered immediately after presentations, a condition that showed nearly errorless performance during the acquisition phase.

**Roediger, Henry L., and Jeffrey D. Karpicke. 2006a. The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science* 1:181–210. [doi:10.1111/j.1745-6916.2006.00012.x][class:journalArticle]**

This comprehensive review discusses the direct and indirect benefits of testing memory and offers readers historical and theoretical perspective related to this educationally relevant research.

**Roediger, Henry L., and Jeffrey D. Karpicke. 2006b. Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science* 17:249–255. [doi:10.1111/j.1467-9280.2006.01693.x][class:journalArticle]**

Studying a prose passage twice enhanced short-term recall performance compared to studying the passage once and taking an initial test on it (81 percent vs. 75 percent); however, this pattern reversed on delayed recall tests given after two days (54 percent vs. 68 percent) and one week (42 percent vs. 56 percent).

**Slamecka, Norman J., and Peter Graf. 1978. The generation effect: Delineation of a phenomenon. *Journal of Experimental Psychology: Human Learning and Memory* 4:592–604. [doi:10.1037/0278-7393.4.6.592][class:journalArticle]**

Often cited as the first report of the generation effect, this article reports multiple experiments in which memory for generated material was superior to material that was simply read, a benefit that occurred across various designs, materials, and outcome measures.

**METACOGNITION**

Although the learning-performance distinction is overwhelming supported by empirical evidence, there appears to be a lack of understanding on the part of instructors and learners alike that current performance is a highly imperfect index of long-term learning; consequently, how we learn is often vastly misaligned with our metacognitive assessments of how we *think* we learn (for a review, see Bjork 1999). Baddeley and Longman 1978, for example, showed that whereas distributing practice was better than massing it for learning typewriter keystrokes, those in the distributed group were relatively less satisfied with their training. That people prefer massed over distributed practice, thinking the former more effective than the latter when, in fact, the opposite is true, has been replicated with other motor tasks (Simon and Bjork 2001), verbal materials (Zechmeister and Shaughnessy 1980), and on tests of inductive reasoning (Kornell and Bjork 2008). Likewise, Roediger and Karpicke 2006 showed that learners mistakenly predicted better long-term learning of prose passages when the passages were restudied multiple times compared to when the passages were tested. Actual learning increased with the number of intervening tests, demonstrating that retrieval practice strengthens the retrieved information, rendering it more likely to be remembered in the future. McCabe 2011, surveying undergraduates, shows the general lack of metacognitive awareness of effective learning strategies to be pervasive: students by and large endorsed learning strategies known to be relatively ineffective for long-term learning. A common theme cutting across all of these studies is that learners tend to favor those conditions that boost short-term performance (e.g., massing, restudying), perhaps thinking, "If it's helping me now, it will help me later." This notion is captured by what Kornell and Bjork 2009 refers to as a stability bias—that people often discount factors that lead to impaired or enhanced learning, instead believing that performance will remain stable across time.

**Baddeley, Alan D., and D. J. A. Longman. 1978. The influence of length and frequency of training session on the rate of learning to type. *Ergonomics* 21:627–635. [doi:10.1080/00140137808931764][class:journalArticle]**

In this study conducted for the British Postal Service, distributed practice was much more effective for long-term learning than massing practice. Subjectively, however, participants were less satisfied in the distributed group because they felt they were falling behind the massed group.

**Bjork, Robert A. 1999. Assessing your own competence: Heuristics and illusions. In *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application*. Edited by Daniel Gopher and Asher Koriat, 435–459. Cambridge, MA: MIT Press. [ISBN: 9780262090339][class:bookChapter]**

Focuses on the potential of learners to misinterpret good performance during acquisition as evidence that long-term learning, as assessed after a delay or on a transfer test, has been achieved.

**Kornell, Nate, and Robert A. Bjork. 2008. Learning concepts and categories: Is spacing the "enemy of induction?"** ***Psychological Science*** **19:585–592. [doi:10.1111/j.1467-9280.2008.02127.x][class:journalArticle]**

Interleaving artists' paintings during a study phase overwhelmingly benefited inductive reasoning—in this case, correctly identifying artists of new paintings—more than blocking their paintings. However, when asked after the induction test which condition helped them learn better, most participants endorsed blocking.

**Kornell, Nate, and Robert A. Bjork. 2009. A stability bias in human memory. Overestimating remembering and underestimating learning.** ***Journal of Experimental Psychology: General*** **138:449–468. [doi:10.1037/a0017350][class:journalArticle]**

Twelve experiments revealed that people are susceptible to a stability bias in human memory, which refers to the tendency to believe that current accessibility of retrieved information (i.e., performance) will remain stable across time, rather than appreciating those factors that may impair or enhance later learning.

**McCabe, Jennifer. 2011. Metacognitive awareness of learning strategies in undergraduates.** ***Memory & Cognition*** **39:462–476. [doi:10.3758/s13421-010-0035-2][class:journalArticle]**

Surveying undergraduates' metacognitive awareness of six effective learning strategies revealed that students are, in general, largely unaware of their benefits. In fact, students were likely to endorse strategies that enhance short-term performance (restudying, massing) as opposed to those that facilitate long-term learning (testing, spacing).

**Roediger, Henry L., and Jeffrey D. Karpicke. 2006. Test-enhanced learning: Taking memory tests improves long-term retention.** ***Psychological Science*** **17:249–255. [doi:10.1111/j.1467-9280.2006.01693.x][class:journalArticle]**

Retention of prose passages, measured one week after the acquisition phase, increased as a function of testing opportunities during acquisition. However, participants predicted the opposite pattern—specifically, that learning after one week would be best when the passage was studied multiple times without being tested, a pattern of performance that was, in fact, demonstrated on the short-term performance.

**Simon, Dominic A., and Robert A. Bjork. 2001. Metacognition in motor learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 27:907–912. [doi:10.1037/0278-7393.27.4.907][class:journalArticle]**

Despite blocking practice leading to better short-term performance of keystroke patterns than interleaving practice, interleaving practice led to greater gains in learning after a delay. Participants receiving blocked practice, however, predicted they would perform better at a delay than did participants receiving interleaved practice, suggesting that participants based their predictions of learning on their current performance.

**Zechmeister, Eugene B., and John J. Shaughnessy. 1980. When you know what you know and when you think that you know but you don't. *Bulletin of the Psychonomic Society* 15:41–44.[class:journalArticle]**

In a list of to-be-remembered words, a second repetition of each item occurred either immediately after its first presentation (massed) or following a number of other items (distributed). Participants predicted that the massed items would be better remembered than the distributed items, whereas actual recall showed the opposite pattern.

**NEUROSCIENTIFIC EVIDENCE**

In addition to the overwhelming behavioral evidence in favor of a learning-performance distinction, there is now empirical support for the notion that learning and performance manifest differently in terms of brain activity. Cross, et al. 2007 employs functional magnetic resonance imaging (fMRI), a procedure that measures brain activity by detecting changes in blood flow, while participants were trained on a simple motor skill under random or blocked practice schedules. Replicating previous behavioral research, random practice impaired performance but facilitated learning relative to blocked practice (see *Distribution of Practice*); additionally, random practice was associated with greater activity in primary motor cortex compared to blocked practice. These results were later replicated and extended by Wymbs and Grafton 2009 using a slightly different experimental design. Similarly, Cohen, et al. 2009 shows that disrupting brain functioning in primary motor cortex during random practice via transcranial magnetic stimulation (TMS), a non-invasive method used to depolarize or hyperpolarize neurons of the brain, greatly diminished retention compared to when TMS was not administered to this region. Importantly, others have shown this detrimental effect of TMS during training to be unique to random practice (i.e., it does not affect retention associated with blocked practice; Lin, et al. 2008; Lin, et al. 2010). More recently, the dorsolateral prefrontal cortex (DLFPC) has also been implicated in the retention benefits conferred by random practice, both in terms of remembering the practiced skill (Kantak, et al. 2010) and performing a new, but related, skill (i.e., transfer of learning; Kantak, et al. 2011).

**Cohen, Nichola Rice, Emily S. Cross, Nicholas F. Wymbs, and Scott T. Grafton. 2009. Transient disruption of M1 during response planning impairs subsequent offline consolidation. *Experimental Brain Research* 196:303–309. [doi:10.1007/s00221-009-1838-x][class:journalArticle]**

Participants performed a sequence task under a random practice schedule while either undergoing transcranial magnetic stimulation (TMS) to primary motor cortex or not. Consistent with the idea that primary motor cortex is involved in the learning benefits conferred by random practice, disrupting its functioning during training with TMS led to poorer long-term retention compared to the non-TMS condition.

**Cross, Emily S., Paul J. Schmitt, and Scott T. Grafton. 2007. Neural substrates of contextual interference during motor learning support a model of active preparation. *Journal of Cognitive Neuroscience* 19:1854–1871. [doi:10.1162/jocn.2007.19.11.1854][class:journalArticle]**

While performing a finger-sequencing task under blocked or random practice schedules, participants underwent functional magnetic resonance imaging (fMRI). During training, random practice, which diminished performance but enhanced later learning compared to blocked practice, was associated with relatively greater blood flow in primary motor cortex.

**Kantak, Shailesh S., Katherine J. Sullivan, Beth E. Fisher, Barbara J. Knowlton, and Carolee J. Winstein. 2010. Neural substrates of motor memory consolidation depend on practice structure. *Nature Neuroscience* 13:923–925. [doi:10.1038/nn.2596][class:journalArticle]**

Transcranial magnetic stimulation (TMS) was administered to either primary motor cortex or dorsolateral prefrontal cortex (DLFPC) immediately after a motor task was trained under constant or variable practice. TMS disruption to primary motor cortex reduced skill retention when practice was constant but not variable, whereas disruption to DLPFC reduced retention when practice was variable but not constant.

**Kantak, Shailesh S., Katherine J. Sullivan, Beth E. Fisher, Barbara J. Knowlton, and Carolee J. Winstein. 2011. Transfer of motor learning engages specific neural substrates during motor memory consolidation dependent on the practice structure. *Journal of Motor Behavior* 43:499–507. [doi:10.1080/00222895.2011.632657][class:journalArticle]**

Transcranial magnetic stimulation (TMS) to primary motor cortex reduced transfer of learning when the original task was practiced under a constant (but not variable) schedule, whereas TMS to dorsolateral prefrontal cortex reduced transfer of learning when the original task was practiced under a variable (but not constant) schedule.

**Lin, Chien-Ho (Janice), Beth E. Fisher, Carolee J. Winstein, Allan D. Wu, and James Gordon. 2008. Contextual interference effect: Elaborative processing of forgetting-reconstruction? A post hoc analysis of transcranial magnetic stimulation-induced effects on motor learning. *Journal of Motor Behavior* 40:578–586. [doi:10.3200/JMBR.40.6.578-586][class:journalArticle]**

Using transcranial magnetic stimulation (TMS) to disrupt brain functioning in primary motor cortex during training eliminated the long-term retention advantage of random versus blocked practice. Without TMS to this brain region, participants showed the typical contextual interference effect—that is, that random practice impairs performance but enhances learning relative to blocked practice.

**Lin, Chien-Ho (Janice), Carolee J. Winstein, Beth E. Fisher, and Allan D. Wu. 2010. Neural correlates of the contextual interference effect in motor learning: A transcranial magnetic stimulation investigation.** ***Journal of Motor Behavior*** **42:223–232. [doi:10.1080/00222895.2010.492720][class:journalArticle]**

Replicating and extending those results provided by Lin, et al. 2008, this study showed that disrupting primary motor cortex exclusively, by using a more spatially focused TMS device, eliminated the long-term retention advantage of random versus blocked practice.

**Wymbs, Nicholas F., and Scott T. Grafton. 2009. Neural substrates of practice structure that support future off-line learning.** ***Journal of Neurophysiology*** **102:2462–2476. [doi:10.1152/jn.00315.2009][class:journalArticle]**

This study replicated Cross, et al. 2007 using a within-subjects design. Compared to practicing finger-sequences in a blocked fashion, a random practice schedule, which was shown to impair performance but facilitate learning, was associated with more blood flow to a brain region known to be involved in movement preparation.

**THEORETICAL PERSPECTIVES**

Decades ago, learning theorists (e.g., Estes 1955; Hull 1943; Skinner 1938; all cited under *Corresponding Conceptual Distinctions*), used terms in their own theories that distinguished between learning and performance. To account for more recent work in the verbal- and motor-learning domains, Bjork and Bjork 1992, in the authors' new theory of disuse, resurrected such a distinction by introducing the terms, "storage strength" and "retrieval strength." Storage strength represents the degree of learning of information or procedures—that is, how integrated the information or procedure is with related information and procedures in memory—whereas retrieval strength represents current ease of access to information and procedures from memory, given current cues. Current performance, which can be observed, is indexed by retrieval strength, whereas learning (which must be inferred) is indexed by storage strength, which acts as a latent variable: it enhances the gain of retrieval strength during opportunities for study or practice and it retards the loss of retrieval strength across time and intervening (interfering) events. In the motor skills literature, specifically, the reloading hypothesis (Lee and Magill 1985) and schema theory (Schmidt 1975) offer highly cited explanations for the learning and performance effects of distributed practice (see *Distribution of Practice*) and varying practice conditions (see *Variability of Practice*), respectively. Finally, the general idea that what can hurt performance can help learning is captured in the Bjork 1994 desirable difficulties framework. Manipulations such as distributing practice, varying the conditions of practice, and testing are "desirable" because they support better long-term retention and transfer compared to their counterpart conditions. They are also "difficult," however, in the sense that these manipulations can impair performance during learning or training and, as a result, are likely to be interpreted as ineffective by students and instructors alike.

**Bjork, Robert A. 1994. Memory and metamemory considerations in the training of human beings. In *Metacognition: Knowing about knowing*. Edited by Janet Metcalfe and Arthur Shimamura, 185–205. Cambridge, MA: MIT Press. [ISBN: 9780585024158][class:bookChapter]**

In this chapter, the desirable difficulties framework is introduced, according to which manipulations that appear to be difficult—objectively and subjectively—during training or learning, can be desirable for long-term retention and transfer.

**Bjork, Robert A., and Elizabeth L. Bjork. 1992. A new theory of disuse and an old theory of stimulus fluctuation. In *From learning processes to cognitive processes: Essays in honor of William K. Estes*, Vol. 2. Edited by Alice F. Healy, Stephen M. Kosslyn, and Richard M. Shiffrin, 35–67. Hillsdale, NJ: Lawrence Erlbaum Associates. [ISBN: 9780805810974]**

The new theory of learning is advocated in this chapter. The terms "storage strength" and "retrieval strength" are used as indices of learning and performance, respectively.

**Lee, Timothy D., and Richard A. Magill. 1985. Can forgetting facilitate skill acquisition? In *Differing perspectives in motor learning, memory, and control*. Edited by David Goodman, Robert B. Wilberg, and Ian M. Franks, 3–22. Amsterdam: Elsevier. [ISBN: 9780080866819][class:bookChapter]**

The reloading hypothesis is advocated to explain the motor learning benefits of interleaving versus blocking practice. Interleaving may encourage "reloading," or reproducing, the motor program needed for to-be-learned skills because the intervening tasks result in a loss of access to those commands. The effortful processing required to reload appears to facilitate learning.

**Schmidt, Richard A. 1975. A schema theory of discrete motor skill learning. *Psychological Review* 82:225–260. [doi:10.1037/h0076770][class:journalArticle]**

A schema theory is postulated to explain the benefits of variable practice on motor learning. It is argued that variable practice fosters long-term learning because it helps one become familiar with the general motor program underlying a skill.