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It's hard to know where to begin with the Bjorks. In his foreword to the US version of my book, Dylan Wiliam describes Robert Bjork as 'the world's leading expert on memory', and yet as a teacher—and therefore someone very much in the memory business—I remained ignorant of the Bjorks' work for 12 years. Robert and Elizabeth's appearance on my podcast was a game changer for me in terms of my thinking about what may well be the ultimate education myth—that learning and performance are the same thing. Moreover, that learning actually benefits from high classroom performance (and the conditions that lead to it). The 10,000+ downloads the podcast has current attracted suggests it was seminal for other listeners too.

It is the Bjorks' focus on what they term 'desirable difficulties' that has most significantly changed my day-to-day classroom practice. Trying to move away from the cosy, comforting conditions that inspire high performance but low learning was a challenge—for both me and my students—for the simple reason that it feels tough. Testing replaced repeated study; interleaved practice replace massed practice; and retrieval of knowledge now takes place over time instead of in nice, tidy blocks. These last two desirable difficulties are the focus of this chapter, and they have profound implications for all teachers and students.

--Craig Barton

The Myth that Blocking One's Study or Practice by Topic or Skill Enhances Learning

Robert A. Bjork and Elizabeth L. Bjork
University of California
Los Angeles, California

As learners, we are often admonished—starting at an early age—to "focus on one thing at a time," to "finish what you started," and so forth. We are urged to be "focused," not "flighty" or "scatterbrained." Such advice seems like good advice, not only as to how we should manage our own efforts to learn, but also how we, as teachers or parents, should manage the instruction of our students or children.

But is such advice good advice? We do know, of course, that individuals can suffer from attention deficit disorder, an inability to stay focused on the task or subject at hand, but that is a different issue than whether one should block or interleave the study or practice of the components of to-be-learned knowledge or skills. In fact, a growing body of research suggests that interleaving, not blocking, enhances the learning and transfer of to-be-learned skills and knowledge. In the remainder of this chapter, we first discuss the evidence that interleaved practice can enhance the learning and transfer of perceptual-motor skills. We then discuss the benefits of interleaving in the domain of verbal/conceptual skills, and we conclude with a brief discussion of theoretical conjectures as to why interleaving can foster long-term retention and transfer of knowledge and skills.

Interleaved Versus Blocked Practice in the Learning of Perceptual-motor Skills

Research on interleaved versus blocked practice of motor skills traces back to a critical study carried out 40 years ago by two kinesiology graduate students (Shea & Morgan, 1979) at the University of Colorado. Shea and Morgan built an apparatus that would let them test the speed and accuracy of participant's ability to release a start button, grab a tennis ball from a slot in the apparatus, knock over three of six hinged barriers in a prescribed order, and then place the tennis ball in a prescribed slot, thereby stopping the timer. There were three such movement patterns to be learned and all participants received 54 practice trials, 18 on each to-be-learned sequence; but those trials were blocked by pattern for half of the participants and interleaved randomly for the other participants.

During the learning phase, blocked practice appeared to be clearly more effective than interleaved practice: Both groups improved across the practice trials, but the participants given blocked practice were able to knock the barriers over in the prescribed pattern more rapidly throughout the practice phase than were the participants given random practice. On a retention test administered 10 days later, however, and whether it was administered under blocked or random/interleaved conditions, the results were very different: When the retention test was administered under interleaved conditions, the blocked-practice group performed far worse than did the interleaved-practice group; and when the retention test was administered under blocked conditions, the difference between the groups was very small, but even then the direction of the difference favored the interleaved-practice group.

Across the intervening years, there have been many replications of the benefits of interleaved over blocked practice for different skills (for a review, see Lee, 2012). To cite just four examples, Goode and Magill (1984) found that interleaved practice enhanced participants' acquisition of the three basic serves in badminton (long, short, and drive) over blocked practice; Jamieson and Rogers (2000) found that people were better able to learn how to carry out different transactions on automated teller machines with interleaved practice versus blocked practice; Hall, Domingues, and Cavazos (1994) found that interleaved practice helped varsity baseball players learn to hit fastballs, change-ups, and curve balls more effectively than did blocked practice; and Ste-Marie, Clark, Findlay, and Latimer (2004) found that children's ability to write cursive letters was enhanced by interleaving the practice of different letters, versus blocking the practice letter by letter, which was how penmanship practice booklets were structured at that time.

The fact that the designers of such penmanship booklets incorporated blocked practice into their booklets reflects the widespread implicit or explicit belief that blocked practice is the way to optimize learning. On a golf driving range, for example, people hit the same shot with the same club over and over again. Batting machines are set up to throw the same pitch over and over again, and basketball players practice shooting from the free throw line or from some other spot over and over again, often with somebody throwing the ball back to them so they do not have to move from that spot.

To the extent that such observations reflect a belief that blocked practice is the way to learn, why might that belief be so pervasive? The short answer is that learners can fail to understand a time-honored distinction in research on learning and memory—namely, the distinction between *learning*, as measured by long-term retention and transfer of skills and knowledge, and *performance*, as measured by the speed or accuracy of executing a to-be-learned skill during the learning process itself (for a review, see Soderstrom & Bjork, 2015). Failing to understand the learning-versus-performance distinction is very problematic because conditions that enhance current performance, such as blocked practice, often fail to enhance learning, as measured by long-term retention or transfer.

A study by Simon and Bjork (2002) in which the participants had to learn three different keystroke sequences on a number pad provides a good illustration of this point. The keystroke patterns differed not only in the keys to be struck, but also in the target completion time for that keystroke pattern. Thus, for example, one pattern required hitting keys 3, 6, 5, 8, and 4 in that order and in a total of 1200 milliseconds, whereas the target times for the two other keystroke sequences were 900 and 1500 milliseconds. Hitting the keys in the target time was the more difficult aspect of the task, and the participants received trial-by-trial feedback as to how their completion time on each trial differed from the target time. Half of the participants received blocked practice—30 trials in succession on each pattern—whereas the other participants received the same 90 trials interleaved randomly. The new wrinkle in the experiment was that the participants, after every five trials on a given pattern, were asked to predict how close they would be able to come to the target movement time for that pattern on a test to be administered in 24 hours were the practice session to stop at that point. What they predicted corresponded to their Day-1 practice performance, which was enhanced by blocked practice, whereas their day-two retention performance was enhanced by random/interleaved practice. Hence, participants receiving blocked practice turned out to be grossly overconfident in their predictions of how well they would perform after 24 hours; whereas participants receiving interleaved practice were far more realistic and accurate in their predictions.

Interleaved versus Blocked Study or Practice of Verbal-Conceptual Procedural Skills and Knowledge

Benefits of interleaving have also been found in the learning of verbal-conceptual knowledge and procedures, including mathematical procedures. In perhaps the first such study, Carlson and Yaure (1990) found benefits of interleaving when participants were asked to learn boolean logic operations. Across more recent years, Rickard, Lau, and Pashler (2008) found that interleaved practice facilitated participants moving from calculating the answers to multiplication problems to achieving direct retrieval of those answers, and Sana, Yan, and Kim (2017) found benefits of interleaving in participants' learning of statistical procedures. In a truly impressive body of research in the domain of mathematics instruction, especially algebra instruction, Rohrer and colleagues have found benefits of interleaving, not only in laboratory studies, but also in actual schools (see Rohrer & Taylor, 2007; Rohrer, Dedrick, & Burgess (2014); Rohrer, Dedrick, Hartwig, & Cheung, 2019; Rohrer, Dedrick, & Stershic, 2015).

Surprisingly, benefits of interleaving have also been found for the inductive learning of categories and concepts, even though in one of the earliest studies in this domain (Kornell and Bjork, 2008), the authors' hypothesis was that inductive learning would be one domain where blocking, not interleaving, would be advantageous. The type of inductive learning of interest was the learning of a category or concept from examples, with the criterion measure being a learner's subsequent ability to identify the category membership of an instance of the category that has not been seen earlier. An example might be a young child recognizing a never-before-seen dog as a dog and not as a cat or some other animal.

Kornell and Bjork's (2008) prediction that blocking would enhance such inductive learning—if not other types of learning—was based on an assertion by the distinguished educational psychologist, Ernst Rothkopf, who said, "spacing is the friend of recall, but the enemy of induction" (personal communication). The logic behind Rothkopf's assertion, which seemed compelling to the authors, is that blocking exemplars would facilitate seeing the commonalities across the exemplars that defined the category, whereas interleaving/spacing would make doing so difficult.

To test Rothkopf's assertion, Kornell and Bjork (2008) designed an experiment in which the participants' task was to learn the styles of different artists from examples of their paintings. Six landscape paintings by each of 12 artists were presented one painting at a time to participants with a given artist's paintings presented either in succession (blocked) or interspersed among paintings by other artists (interleaved). On the final test new painting were shown one at a time, and the participants were asked to identify who, among the 12 artists (whose names were provided) had painted a given new painting.

To the authors' considerable surprise, interleaving—not blocking—enhanced the participants' inductive learning of the different artists' styles. What made those findings especially interesting was that, after the final test, when the participants were asked what helped them learn better, interleaving or blocking, they predominantly said blocking (massing), even though they, as shown in Figure 1, had just completed a test on they had, predominantly, identified the new paintings by interleaved artists more accurately than they did the new paintings by blocked artists. As shown in Figure 1, about three-quarters (78%) of the participants were better identifying new paintings by the interleaved artists, whereas about three-quarters of the participants (78%) said that blocking was as good or better than interleaving in helping them learn an artist's style.

In subsequent research using the paintings task, Kornell, Castel, Eich, and Bjork (2010) replicated Kornell and Bjork's (2008) experiment, but with older-age participants as well as with college-age participants. In advance of carrying out the research, there were reasons to think that older participants might need the support of blocking—that, when shown a painting in the interleaved condition, they might be less able than younger participants to remember the prior paintings by that artist, whereas blocking would foster such comparisons. What Kornell et al. found, however, was that the older participants profited from interleaving to about the same extent as did the younger participants. Children, too, appear to profit from interleaving. Vlach, Sandhofer, and Kornell (2008) found benefits of spacing/interleaving when children—after being shown examples of novel objects that were labelled with names such as "wug"—were then later asked to pick out the wug from among a set of four objects that included a version of a wug not presented earlier. Vlach and Sandhofer (2012) also found that children's learning of science concepts benefited from spacing/interleaving.

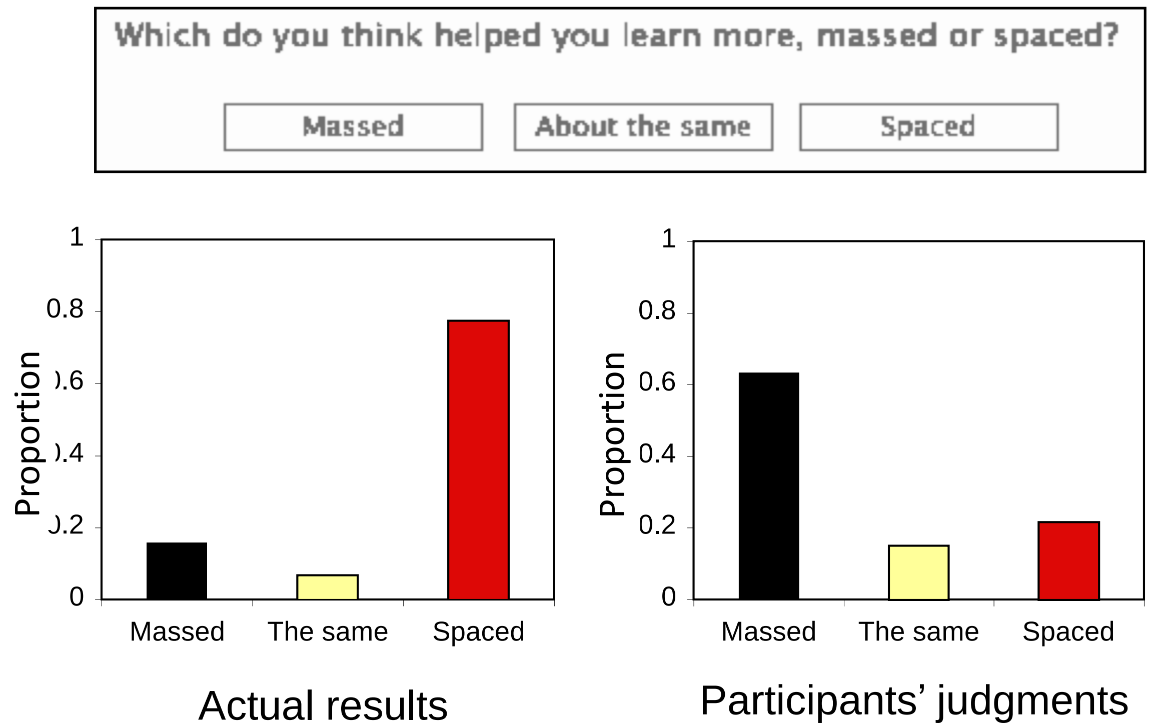

Figure 1. Proportions of participants (left panel) who were better at identifying new paintings by artists whose paintings had been presented massed/blocked versus spaced/interleaving versus the proportions of participants (right panel) who judged they had done better identifying new paintings in the corresponding conditions. Adapted from "Learning concepts and categories: Is spacing the 'enemy of induction'"? by N. Kornell and R. Bjork, 2008, *Psychological Science, 19*, 585–592.

Whether pure interleaving is more effective that combine blocking and interleaving was explored by Yan, Soderstrom, Seneviratna, Bjork, and Bjork (2017). More specifically, Yan et al. wondered whether, using the paintings task, there might be hybrid schedules, such as first presenting a few of the artist's exemplars in a blocked manner before then moving into an interleaved presentation schedule for the remainder of that artist's exemplars (or the other way around: that is, going from interleaved to blocked), that would capture benefits of both types of schedules. They found that a blocked-to-interleaved schedule was better than pure blocking (which was the least effective of the schedules they examined) and as effective, statistically, but not better than, pure interleaving. In other experiments they examined participants' pre-experimental beliefs about what kind of schedule might be best for such inductive learning. The participants demonstrated some sophistication by not endorsing pure blocking, versus certain hybrid schedules, but pure interleaving was the least favored of all the schedules mentioned, despite its being the most effective schedule, overall.

In subsequent research, Yan, Bjork, and Bjork (2016) carried out multiple experiments designed to explore what experimental manipulation might "dislodge" participants' belief that blocking, not interleaving, enhances the inductive learning of painters' styles in the Kornell and Bjork's (2008) task. In one experiment, the participants, before being asked at the end of the experiment what helped them learn the artists' styles better, blocking or interleaving, were told that 90% of participants in the paintings task are better at identifying new paintings by the interleaved artists than they are at identifying new paintings by the blocked artists. After getting that message, 60% of the participants still said that blocking was as good or better than interleaving.

Even when participants in another condition were told that not only do most people do better with interleaving, but also (a) why the sense that blocking helps one see the defining characteristics of a given artist's paintings is misleading and (b) why interleaving helps seeing the differences between artists, which is a "crucial" factor in learning the artists' styles, only about half the participants said that interleaving helped them learn the artists' styles. When participants were given feedback as to their actual performance ("You got X/24 of the blocked artists correct, and you got Y/24 of the interleaved artists correct. You did better on the [blocked/interleaved] artists") and then asked to say why by selecting between (a) "that particular set of artists was easier to learn" and (b) "that schedule is more effective," 58% of the 45 participants who did better on the interleaved artists said that those artists were easier to learn, whereas 80% of the 20 participants who did better on the blocked artists said that the blocked schedule was more effective. Finally, when participants were asked to say what schedule they would use in teaching students if they were an art teacher, twice as many participants (50 versus 25) said a blocked schedule as said an interleaved schedule.

So why do most participants think that blocking the exemplars of a given category enhances inductive learning? One factor, alluded to already, is that blocking creates a sense of fluency with respect to noticing the similarities across a given artist's paintings, whereas interleaving creates a sense of confusion and difficulty in noticing those similarities. Another factor is that participants are likely to come to the experiment with a belief that blocking is good—because blocking is so commonly used in real-world settings, including by the participants' teachers. That participants come to such an experiment with the belief that blocking, not interleaving, fosters inductive learning is supported by the results of an experiment by Tauber, Dunlosky, Rawson, Wahlheim, and Jacoby (2012). In Tauber et al.'s experiment the participants learned eight families of birds (warblers, finches, etc.) and were shown pictures of members of these families, one bird at a time. After a picture was shown, they saw a message, such as "you have just studied a Jay"; "click on the bird family that you would like to see next." Overwhelmingly, participants chose to see another picture in the same family—that is, another picture of a Jay in this example.

The benefits of spacing/interleaving have been shown in the inductive learning of other categories as well, such as species of butterflies (Birnbaum, Kornell, Bjork, & Bjork, 2013), and how such benefits are modulated or eliminated by various manipulations has been explored (see, e. g., Kang & Pashler, 2012; Wahlheim, Dunlosky, & Jacoby, 2011). In a potentially important new context, foreign-language learning, Pan, Tajran, Lovelett, Osuna, and Rickard (in press) found that the learning of Spanish-language verb conjugations profits from interleaving.

To conclude this section it is important to mention that Rothkopf—in saying that spacing is the enemy of induction—was not entirely wrong. In fact, in their discussion, Kornell and

Bjork (2008) asserted—notwithstanding the benefits of interleaving they found in the inductive learning of painters' styles—"there surely are situations in which massing is more effective for induction than is spacing" (page 590), and they report an experiment designed to illustrate the point. Participants had to figure out and remember for a later test the single word that could fill in the blanks before a set of other words, such as "_____ cracker, _____ wood, _____ side, _____ ant, _____ truck, _____ arm," where the answer in this case is *fire.* Spacing/interleaving of such materials made it extremely difficult to solve such problems and massing, not spacing led to better end-of-experiment recall of the words that solved the 12 such problems. Kornell and Bjork concluded by saying "… whether spacing is the friend or enemy of induction is a matter for sophisticated theorizing, because induction is a product of conceptual and memory processes that are open to multiple situational influences," but "that in less contrived and more complex real-world learning situations, spacing appears to facilitate induction" (Page 591).

Such conceptual and memory processes have been explored by Carvalho and Goldstone (2014, 2015) in a systematic program of experiments, most requiring participants to learn categories of "blobs" based on identifying perceptual features of such shapes that distinguished one category of blobs from another category. Across that program of research Carvalho and Goldstone have demonstrated that when the biggest challenge confronting learners is to identify the feature(s) that define a category, versus distinguish between categories, blocking—not interleaving—tends to enhance such inductive learning. That conclusion bears on the question taken up in the next section of this chapter, namely, why and when—from a theoretical standpoint—does interleaving support long-term retention and transfer?

Why Does Interleaving Support the Long-term Retention and Transfer of Knowledge and Skills?

In the domain of learning motor skills, the idea that the "contextual interference" caused by interleaving to-be-learned skills—while depressing momentary performance—sets the stage for enhanced learning (Battig, 1979) has been very prominent, especially after Shea and Morgan (1979), motivated by Battig's ideas, provided the demonstration experiment discussed earlier in this chapter. As embellished by Shea and Morgan and by Shea and Zinny (1983) in their *elaboration and distinctiveness hypothesis,* the benefits of interleaving result from the contrasts and comparisons that are evoked during an interleaved schedule, but not, or at least to a much lesser extent, during a blocked schedule. Such contrasts and comparisons then lead to more elaborative and distinctive processing, which, in turn, enhances long-term retention and transfer.

An alternative interpretation is the *forgetting and reconstruction hypothesis* or *reloading hypothesis* (Lee & Magill, 1983, 1985). The basic idea behind this hypothesis is that during blocked practice, forgetting or interference between trials is minimal; whereas with interleaved practice, the switching between or among the to-be-executed skills requires a reloading of the to-be-executed motor program, thereby providing more effective practice for a post-training test of retention or transfer. Cuddy and Jacoby (1982) argued for, and provided evidence for, much the same idea in the domain of verbal learning. For an excellent review of contextual interference effects and interpretations, see Lee (2012).

In the domain of learning mathematical concepts and procedures, Rohrer and colleagues (e.g., Rohrer, Dedrick, Hartwig, & Cheung, 2019) have argued for—and provided convincing evidence for—the idea that interleaving enhances learners' ability to select the appropriate procedure when confronted with a problem to solve on a post-instruction test of retention or transfer. Thus, for example, a mathematics workbook that presents a series of problems all to be solved via the Pythagorean Theorem provides students with a kind of crutch—in effect—telling them what procedure to draw on to solve any one of the presented problems. On some later post-instruction test that really matters, however, no such crutch will be provided. That is, different types of problems will typically be presented in a more or less random order on such tests and the procedure to use in solving each of them will not be specified. In other words, while interleaved instruction and practice exercises processes that will be crucial for achieving good performance on post-instruction tests of retention and transfer, blocked practice does not.

Finally, in the domain of learning concepts and categories, there is evidence—alluded to earlier—that interleaving can draw attention to and enhance the encoding of features that distinguish between the exemplars of different categories and concepts.

Concluding Comments

In the context of real-world education, the potential of interleaving to enhance the effectiveness of instruction and self-regulated learning seems very substantial, even exciting. Much of relevance to real-world education still needs to be determined, however, such as the chunk size, so to speak, of the materials to be interleaved, and the extent to which the interleaved materials should or should not be related and potentially confusable. And then there is the biggest hurdle of all: Convincing students and teachers that interleaving is good for them, despite the facts that it poses difficulties, often leads to worse performance during instruction than does blocked practice, and differs from what students, teachers, and parents have experienced in the past. It is in that domain that the audiences for this book—teachers, students, and parents—have an important role to play.

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