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REVIEW ARTICLE

Distributed Learning: Data, Metacognition, and Educational Implications

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Abstract A major decision that must be made during study pertains to the distribution, or the scheduling, of study. In this paper, we review the literature on the benefits of *spacing*, or spreading one's study sessions relatively far apart in time, as compared to *massing*, where study is crammed into one long session without breaks. The results from laboratory research provide strong evidence for this pervasive "spacing effect," especially for long-term retention. The metacognitive literature on spacing, however, suggests that massing is the preferred strategy, particularly in young children. Reasons for why this is so are discussed as well as a few recommendations regarding how spacing strategies might be encouraged in real-world learning. While further research and applicability questions remain, the two fields—education and cognitive science—have made huge progress in recent years, resulting in promising new learning developments.

Keywords Spacing effect · Distributed learning · Distributed practice · Massing · Metacognition · Motor learning

More and more, and as evidenced by this set of articles, cognitive psychologists are aiming to translate their findings into educational contexts, bridging a gap between basic research and the field of education. In the past, these fields have typically worked in parallel, with, for instance, researchers examining learning in laboratories and educators promoting learning in classrooms. The goals of this paper are to review data related to the *distribution* of study and, in particular, to examine the applicability of spacing benefits to the real world, both inside and outside of the classroom.

A major decision that must be made during study pertains to the distribution, or the scheduling, of study. Learning is rarely successful with only one study session, and after having already studied a particular topic, individuals must decide how long to wait before re-studying

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the same information. Over the last century, one learning strategy in particular has shown to be enormously consistent in the laboratory in terms of improving test performance: distributing study sessions far apart during study. Known formally as *spacing*, this strategy—of waiting for relatively longer periods of time before re-study—has led to improved performance, as compared to a *massing* strategy, where the individual will study again immediately, for a total of one long study session (for a review, see Cepeda *et al.* 2006).

Distribution of practice has been of concern to investigators of learning at least as far back as Ebbinghaus (1885). Ebbinghaus, using himself as a subject, studied a list of meaningless syllables. He presented half of the syllables to himself using massed practice, repeating study within 1 day, and the other half using spaced practice, repeating study across 3 days. His results showed that there were more savings when re-learning the syllables if study had spanned 3 days. That is, the re-learning process was shorter after spaced practice than after massed practice. Ebbinghaus (1885) concluded: "…with any considerable number of repetitions a suitable distribution of them over a space of time is decidedly more advantageous than the massing of them at a single time" (p. 89). A little over 10 years later, Jost (1897) formulated his *Law of Forgetting*: If two memories are of equal strength but different ages, the older one will benefit more from an additional learning trial. Within a few decades, Ruch (1928) published the first meta-analysis on the spacing effect. Even in his early review, he lists at least 25 studies, and with many more conditions, describing the advantages of spacing over massing.

One might guess that a finding so consistent and full of history would influence the educational field rather quickly. A finding that has encompassed the learning strategies tested in people of all ages, starting with infants, all the way to adults (Bahrick 1987; Bjork 1979; Cahill and Toppino 1993; Dempster 1987; Glenberg 1979; Rea and Modigliani 1987; Toppino 1991, 1993; Toppino and DiGeorge 1984), should certainly be fitting for real-world learning. Indeed, for many researchers, the deeper goal has been to apply spacing strategies to the learning habits of students in school. On the contrary, word about the benefits of spacing was slow to spread (e.g., Dempster 1988). Some researchers perhaps thought that the lack of spaced practice in educational and other practical settings was due to the formal language of researchers who had published their findings in less accessible, psychology journals. Consider, for instance, why Neisser felt that a cute limerick about the spacing effect was necessary at a public conference: "You can get a good deal from rehearsal, if it just has the proper dispersal. You would just be an ass, to do it en masse. Your remembering would turn out much worsal." (Re-quoted in Bjork 1988, p. 399).

Furthermore, even after acknowledging the benefits of spacing, changing teaching practices proved to be enormously difficult. Delaney *et al.* (2010) wrote: "Anecdotally, high school teachers and college professors seem to teach in a linear fashion without repetition and give three or four noncumulative exams." (p. 130). Focusing on the math domain, where one might expect a very easy-to-review-and-to-space strategy, Rohrer (2009) points out that mathematics textbooks usually present topics in a non-spaced, non-mixed fashion. Even much earlier, Vash (1989) had written: "Education policy setters know perfectly well that [spaced practice] works better [than massed practice]. They don't care. It isn't tidy. It doesn't let teachers teach a unit and dust off their hands quickly with a nice sense of 'Well, that's done.'" (p. 1547).

Understandably, the bulk of research on the distribution of learning has remained focused on the individual and in the laboratory, rather than the classroom, and unfortunately, often at the expense of realism, the majority of methods have used rather arbitrary materials, such as nonsense syllables (Jost 1897; Perkins 1914), digit lists (Robinson 1921), or lists of words (see Janiszewski *et al.* 2003, for a review). Moreover, in their recent review, Delaney *et al.*

(2010) wrote: “No one is inherently excited about word lists, but they have been used in the preponderance of studies on the spacing effect…” (p. 65).

Our objective here is to provide pertinent data on the spacing effect that might be considered useful for applications to education, and to conclude with a few recommendations for both educators and students. We acknowledge that the process of changing educational practices can be a very slow one. However, one aspect of implementation we focus on will be on how an individual learns, and not necessarily on how a teacher should teach. We begin with brief reviews of the spacing effect, in the cognitive and motor domains, and then go into a broader discussion of the spontaneous, or metacognitive, choices of the individual, both in adults and in children.

The Spacing Effect: Data and Mechanism

Following Ruch's (1928) review, such a plethora of studies regarding the distribution of study ensued that now more than a handful of review papers have been published (e.g. Cepeda *et al.* 2006; Crowder 1976; Dempster 1989; Delaney *et al.* 2010; Donovan and Radosevich 1999; Greene 1992; Janiszewski *et al.* 2003; Pavlik and Anderson 2003). The results of these reviews have led to the summation that while there are some complicated issues that still continue to be examined—such as the difference in retention interval (how long the break is between study and test) and the interstimulus interval (how long breaks are between study sessions)—by and large, for long-term retention, spaced study leads to better performance than uninterrupted, massed study.

In the 1960s, the first substantial empirical differences between massed practice and distributed practice—dubbed MP and DP, respectively—were established (Peterson *et al.* 1962, 1963). Results showed that when word–number pairs were presented for various amounts of time and number, cued-recall performance following DP was significantly better than that following MP. Underwood's (1970) data also supported the early spacing benefits by showing that the effect strengthens with repetition. In that same paper, Underwood (and see also Melton 1970) brought to light that the spacing effect would shatter the certainty of the *total-time law*, which stated that the amount learned is a direct function of study time regardless of how that time is distributed.

While data supporting the spacing effect were being accumulated, researchers examined potential reasons for spacing benefits. Bjork and Allen (1970), for example, examined two possible mechanisms: better consolidation at trial 1 or stronger encoding at trial 2. By varying the difficulty of the intervening task (coming between study trial 1 and study trial 2), they found that the spacing effect seemed to be due to better encoding at trial 2. In fact, final recall performance was slightly, but consistently, better when the intervening task was difficult, as compared to easy. This result could be seen as a precursor to later theories related to *desirable difficulty* (Cuddy and Jacoby 1982; Glover 1989; Schmidt and Bjork 1992; Whitten and Bjork 1977), where the more difficult it is to retrieve the item at the second trial (as a result of longer elapsed time since original study), the more easily that item would be retrieved again later (at a long-term test). This mechanism was also related to the classic *contextual variability* explanation (Estes 1955; Glenberg 1979; Raaijmakers 2003), where the context is encoded—and thus used as a retrieval cue—along with the item, resulting in a less redundant study environment for a spaced study trial, as compared to a massed study trial.

The mechanisms of contextual variability and desirable difficulty would indicate that spacing one's study far apart in time would be increasingly helpful. However, there were some results suggesting that intervening time may sometimes be *too long*, and spacing could hurt study. In Landauer and Bjork's (1978) study, participants were presented with cue-target pairs using what was called an *expanding study schedule*—where the distribution of study started out rather small (maybe one intervening item, or even completely massed)—when study would be rather effortless—and then over three repetitions, grew to sometimes ten intervening items. The performances of these individuals were compared to those of participants that had uniformly—and quite lengthy—spaced study from the outset, and results showed a small but significant benefit of expanding practice (see also Cull *et al.* 1996). One difference between the expanding practice paradigm and previous paradigms was that, in this case, the study trials were not in fact straight study trials, but rather, test trials (cue-only trials), without feedback. Thus, the results might not be too surprising: If you cannot remember the target at a very long delay, *and are not provided with feedback*, then there is a slim to none chance that you will remember that target suddenly on a later test. (We discuss briefly again the issue of spacing and testing later.)

More recent reports, however, find no difference between the expanding and spaced study trials (Balota *et al.* 2006; Carpenter and DeLosh 2005; Cull 2000), and interestingly, the same discrepancy was found years earlier (see Ruch 1928, for a summary). Even at present, while no strong conclusions regarding expanding practice have been made, some believe that an expanding study strategy would be one that would be most easily applied to real-world study, particularly when motivation or retrieval success is low (see Cull *et al.* 1996), and when test trials (not simply passive study trials) can be incorporated. A roadblock that remains, in these and other studies, and has been commonly mentioned, is to think of ecologically valid methods in which to extrapolate data that would cover learning over a much longer time period, rather than a few seconds or minutes, as is typical in the laboratory (e.g., Crowder 1976; Dempster 1988; Glenberg 1979; Hintzman 1974).

While the bulk of the laboratory data have examined learning over extremely short time periods, Bahrick *et al.* (1993) were the first to have participants commit to a 9-year-long investigation of spacing. Participants were given English—foreign vocabulary word pairs to learn, at either massed or spaced study sessions. Results showed that, while learning was considerably slower and more difficult during spaced study, at final performance—which was up to 5 years following the termination of training—the data flipped: Spaced study was significantly more beneficial than massed study in the end. They included in their discussion an earlier quote from Schmidt and Bjork (1992): "Manipulations that maximize performance during training can be detrimental in the long term; conversely, manipulations that degrade the speed of acquisition can support the long-term goals of training." (p. 207). We discuss this potential misperception further in the "Metacognition and the Spacing Effect" section later on. This conclusion can also be connected to the notion of desirable difficulties. If learning feels too quick and easy—as it would during massed study more so than during spaced study (where some forgetting has already occurred)—it may be used as a warning that forgetting might occur more rapidly in the long run [although see Koriat (2008) regarding complexities of easy learning leading to easy remembering].

Another hypothesis for why the spacing effect occurs has been the notion that during massed study, we habituate, or do not process the information as thoroughly as the stimulus continues to present. Known as the *deficient-processing theory* (Bregman 1967; Cuddy and Jacoby 1982; Greeno 1970; Hintzman 1976), this assumes that during spaced study, closer attention is paid to the item at the elapsed study trial and, thus, deeper processing would have taken place. Consider the following analogy: If a stimulus, say, noisy traffic outside your window, is presented to you continuously for a long period of time, eventually, you will learn to ignore that noise. If the traffic noises came once every half hour, they would be quite noticeable and, thus, more deeply processed. Support for the deficient-processing theory also comes from animal learning tasks, such as the Morris water maze, where animals have to find a platform in a tank of opaque water. Data have shown that spaced learning trials lead to better long-term memory than massed learning trials (Commins *et al.* 2003; Spreng *et al.* 2002). Sisti *et al.* (2007) found similar results and, furthermore, found that training with spaced trials induced a more persistent memory which, crucially, was related to the number of new cells that survived in the hippocampus. Put differently, one might view spacing as a way of allowing brain cells to "regenerate" between study sessions. This would be less likely during massing. Consider also a different analogy, where one is performing a motor task: If we were to mass our physical training for too long, our muscles would not have time to recharge, and would fail to get the full benefits of the ongoing training. In the next section, we touch upon a few comparison spacing data in the action literature.

Analogy to Action: Data and Mechanism

Given the comparison of the brain cells habituating to muscles tiring out, it seems logical that spacing effects would be substantial during motor tasks. However, there have been several findings in the literature that propose that spacing boosts rely on explicit, and not implicit, functions (Jacoby and Dallas 1981; Perruchet 1989; Roediger and Challis 1992). For example, in Challis and Brodbeck (1992), when participants had to fill in a word fragment (e.g., –l-ph—t) during either massed or spaced study, the spacing effect went away. In another study, Challis (1993) participants studied words either massed or spaced, but also had different levels of intent of learning. Some were in the *intentional* condition—where, like in most other studies, the intent was to learn the words for a later test. Some were in an *incidental-semantic* condition, where they had to rate the words for pleasantness, and the final group was in the *incidental-graphemic* condition, where they simply had to count ascending or descending features of letters in the word, alphabetically, as compared to a probe letter (i.e., for the word "window" and probe "m," the number of letters falling after—ascending—would be four). Results showed that the spacing effect was *unobservable* in the final condition. In short, the spacing effect seems to be a product of explicit, effortful processing, particularly during the second study session. Given that implicit processes do not reap the same benefits, this generality leads to the prediction that the benefits of spacing might not hold up during motor learning tasks, since motor skills are often thought of as being based on implicit learning (Anderson 2000). Thus, in the motor behavior and skilled behavior domains, there are some additional considerations leading to the necessity of a somewhat more nuanced account of and recommendations about spacing in motor and procedural learning scenarios that arise from the verbal literature (e.g., Rohrer and Pashler 2010).

Perhaps even prior to the empirical work on cognitive learning and the spacing effect, the benefits of spaced study had been apparent in an array of motor learning tasks, including maze learning (Culler 1912), typewriting (Pyle 1915), archery (Lashley 1915), and javelin throwing (Murphy 1916; see Ruch 1928, for a larger review of the motor learning tasks which reap benefits from spacing; see also Moss 1996, for a more recent review of motor learning tasks). Thus, as in the cognitive literature, the study of practice distribution in the motor domain is long established (see reviews by Adams 1987; Schmidt and Lee 2005), and most interest has centered around the impact of varying the separation of learning trials of motor skills in learning and retention of practiced skills. Lee and Genovese (1988) conducted a review and meta-analysis of studies on distribution of practice, and they concluded that massing of practice tends to depress both immediate performance and learning, where learning is evaluated at some removed time from the practice period. Their main finding was, as in the cognitive literature, that learning was relatively stronger after spaced than after massed practice (although see Ammons 1988; Christina and Shea 1988; Newell *et al.* 1988 for criticisms of the review).

Apart from spacing within sessions, just as with Bahrick's work on verbal learning scenarios (e.g., Bahrick *et al.* 1993), people have looked at the benefits of spacing across learning sessions as well as within sessions. Probably the most widely cited example is Baddeley and Longman's (1978) study concerning how optimally to teach postal workers to type. They had learners practice once a day or twice a day, and for session lengths of either 1 or 2 h at a time. The main findings were that learners took the fewest cumulative hours of practice to achieve a performance criterion in their typing when they were in the most distributed practice condition. This finding provides clear evidence for the benefits of spacing practice for enhancing learning. However, as has been pointed out (Newell *et al.* 1988; Lee and Wishart 2005), there is also trade-off to be considered in that the total elapsed time (number of days) between the beginning of practice and reaching criterion was substantially longer for the most spaced condition. Thus, while spacing may boost learning, it may be thought to be relatively inefficient in terms of study time. As we discuss later, this feeling of inefficiency may be one of the reasons that spacing is not the more popular strategy.

Interestingly, in that same study (Baddeley and Longman 1978; and see also Pirolli and Anderson 1985 and Woodworth and Schlosberg 1954), there was evidence of such a thing as *laboring in vain*. That is, exceeding a certain number of hours of practice a day (more than approximately 2 h) led to no increases in learning, as might be expected. Related to the deficient-processing theory mentioned above, these results are crucial in understanding intuitively how the spacing effect works: We simply get burnt out. These data are also analogous to the cognitive literature on *overlearning*, which shows that while continuous study over long periods of time might seem beneficial (and even feel good) in the short-term, the benefits disappear soon afterwards (Rohrer *et al.* 2005; Rohrer and Taylor 2006).

Motor learning may also be somewhat more complicated than cognitive learning in that there are different types of learning measures. For instance, Lakshmanan *et al.* (2010) looked at the different kinds of learning that can take place within the context of new product use such as in gadgets like smartphones or gaming consoles. They found that in terms of completion time for a target action on a new software package, for participants whose study involved repeated exposure to the instructions (i.e., verbal learning), spaced practice led to shorter execution times than massed practice. However, when study involved an initial exposure to the instructions followed by repeated opportunities to actually use the software (i.e., experiential learning), massing supported faster performance on test trials than did spaced practice. Thus, spacing benefits are not always obvious when it comes to actions.

One of the most obvious distinctions between the standard paradigms of verbal learning and motor skill acquisition has to do with the to-be-learned material occurring in isolation or in the presence of other materials. Beginning as far back as Ebbinghaus's (1885) work on list learning, spacing in verbal learning has involved multiple presentations of single items, or word-pairs, separated not simply by the passage of time, but by intervening presentation of other to-be learned items (e.g., dog, light, tent, dog). In contrast, studies of spacing in motor skills have more typically involved trials of a single, to-be-learned task, with varying separations between trials. Thus, at some level, though common language is applied to the two paradigms, they are structurally quite different, and thus it is not surprising that the basic effects in the two areas are not entirely equivalent.

That said, there is a paradigm within the motor and procedural learning paradigm, which arguably is more similar to the arrangement in the typical verbal list learning domain (see, e.g., Schmidt and Bjork 1992) and that is contextual interference. Contextual interference was first put forward as a construct for verbal list learning by Battig (1966, 1972), but was soon borrowed and became quite prominent in the motor learning domain because of work by Shea and Morgan (1979). In their original study, Shea and Morgan had people practice three similar, but distinct, discrete motor tasks in one of two different practice structures. Blocked practice involved working through a predetermined number of trials of one of the tasks before moving to the second task, and so on—similar to massed practice. In contrast, random practice involved a semi-random ordering of trials so that no more than two consecutive practice trials were of the same task, and thus typically other to-be-learned material was interleaved between trials of a given task. The main finding was that during the practice/learning phase, performance under blocked practice conditions was superior to that under random practice conditions; however, on the long-term retention test, *this pattern was reversed*. As in the cognitive data, easy learning—as in the massed or blocked condition—did not translate into best retention. These findings should have huge implications for real-world learning, especially if individuals have the illusion that "easy learning now means better retention later."

The same basic results have been repeatedly demonstrated in the decades since (see reviews by Magill and Hall 1990; Lee and Simon 2004), and with a wide variety of motor tasks including different badminton serves (Goode and Magill 1986), rifle shooting (Boyce and Del Rey 1990), a pre-established skill, baseball batting (Hall *et al.* 1994), learning different logic gate configurations (Carlson *et al.* 1989; Carlson and Yaure 1990), for new users of automated teller machines (Jamieson and Rogers 2000), and for solving mathematical problems as might appear in a class homework (Rohrer and Taylor 2007; Le Blanc and Simon 2008; Taylor and Rohrer 2010). In a similar vein, Kornell and Bjork (2008) showed that even for induction tasks—identifying novel instances of work by artists—interleaving presentation of exemplars with those of other artists during a study phase supported better performance than massing those from a given artist together. This result in particular is rather counterintuitive, since it would seem likely that the opportunities for close comparison and contrast afforded by massing would have yielded better identification of the new works.

Clearly, when multiple things are to be learned—arguably the case in almost any educational setting, formal or informal—interleaving (or allowing for distributed exposure to materials) seems to be beneficial to long-term learning. Moreover, this holds true for both cognitive and motor learning. In the next section, we take a look at the generality of the spacing effect, focusing on its strength in young children.

The Spacing Effect: Development, Applicability, and Universality

Does the spacing effect obtain in young children? In general, the resounding answer seems to be a yes. Using both recognition tasks (Cahill and Toppino 1993; Rea and Modigliani 1987; Toppino *et al.* 1991; Vlach *et al.* 2008) and free recall tasks (Seabrook *et al.* 2005; Toppino 1991, 1993; Toppino and DeMesquita 1984; Toppino and DiGeorge 1984; Wilson 1976), benefits of spacing have been apparent in children of all ages (see Fig. 1 for an example of the spacing effect in 3- and 4-year-old children—created from data presented in Table 2 of Toppino and DeMesquita 1984). In fact, the effect has also been tested in infants, with positive results (Cornell 1980; Galluccio and Rovee-Collier 2006; Vander *et al.* 1985). For instance, using a habituation procedure (Cornell 1980)—where infants will look longer

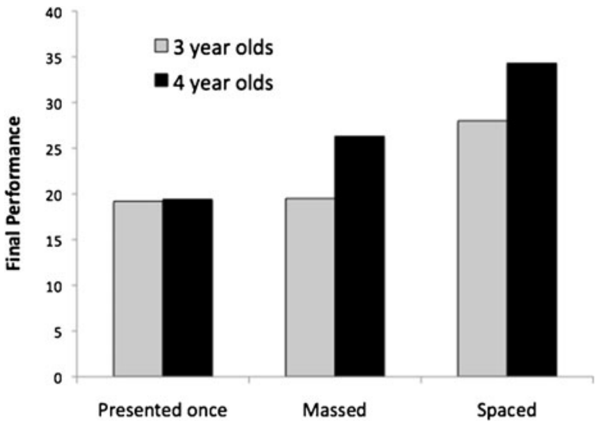

Fig. 1 Final test performance scores for 3- and 4-year-olds after having massed study, spaced study, or seen items presented only once (created from data presented in Table 1 of Toppino and DeMesquita 1991)

at novel or unfamiliar objects—the data showed that after massed and spaced viewings of photos, and after a delay that ranged from 1 min to 1 h, babies tended to look longer at the massed-studied photos, suggesting that they had forgotten to a larger degree those photos than the spaced-studied photos.

Consistent with the issue introduced above describing the hypothesis that the spacing effect would occur only under explicit conditions, Toppino *et al.* (2009b) found that children between preschool age and college students exhibited the spacing effect for *intentional* learning conditions, where they are studying with the goal to perform well on a later test. However, interestingly, this finding reversed for the very young children on an *incidental*, or implicit task, indicating that the effect occurs in young children only when they voluntarily engage in elaborate semantic processing. Thus, while the spacing effect seems to hold across ages, starting from infancy, the mechanism for, and thus, the particular contexts under which it occurs is still under investigation.

Many have begun to look at the success of spaced study inside the classroom, as well as with classroom materials, agreeing with Ruch's (1928) early statement that the spacing effect was clearly meant for the classroom. Even earlier, Pyle (1915) found, for instance, that arithmetic facts were recalled better by children drilled once a day for 10 days than by those who were drilled twice a day for 5 days. (Although both are considered spaced study sessions, it is worthy of note that the longer lapses between study trials led to an increase in performance.) In 1934, English *et al.* found better learning when a text was read at 3-h intervals rather than in succession (English *et al.* 1934). Much later, Reynolds and Glaser (1964) also found the spacing effect to occur when learning science concepts. In another early study (Gay 1973), the spacing effect was found when studying arithmetic. Thereafter, the effect was found when studying vocabulary (Dempster 1987) and during text processing (Dempster 1996; Glover and Corkill 1987; Kraft and Jenkins 1981). In addition, much more recently, Vlach and Sandhofer (2012) found that children as young as 5–7 years of age also benefitted from spaced study when learning science lessons. Their conclusion was that spacing promotes various types of learning—analogous to an increase in contextual processing—while massing does not.

The spacing effect has also been linked to the testing effect (as is apparent in the expanding practice paradigm described previously) and, thus, will be influenced by whether the trials are study or test (with and without feedback) trials. For the most part, with the addition of testing trials—either at massed or spaced delays—the spacing effect holds true. For instance, Rea and Modigliani (1987) looked at spelling performance using expanding versus spaced study and found benefits for spaced study. In general, as others in this issue will cover, testing has significant effects on long-term retention (e.g., Agarwal *et al.* 2008) and, in tandem with the spacing strategy, is likely to lead to accrued boosts in learning (e.g., Pashler *et al.* 2007).

The spacing effect has not, however, proven to be universally obtained, particularly in the classroom (for an early review, see Dempster 1988). We focus here on a crucial factor that arises in both the classroom and the laboratory—to which we have only but alluded: the issue of *immediate* versus long-term performance measures. Thus far, we have presented data displaying directly the benefits for *long-term* retention. However, in the classroom, there may be many instances where short-term performance is also important. Revisiting the data from both the cognitive and motor learning literature, where massing is more efficient, or feels better *during learning*, the superior nature of spacing suddenly becomes doubtful. Early on, for instance, Austin (1921) found that when reading texts, spaced study was no better than massed study, when comprehension was measured immediately—although the spacing effect did obtain at a longer delay (note that massing was not more effective than spacing).

There is other evidence for a reversal of the spacing effect when the test *immediately* follows acquisition. In other words, when the test is coming up very soon, massed practice has been shown at times to be more advantageous than spaced practice (e.g., Bregman 1967; Lee and Genovese 1988; Lee and Magill 1983; Shea *et al.* 1990). Termed the *proportionality rule* by Glenberg and Lehmann (1980), it proposes that "when the retention interval is short relative to the spacing of the repetitions, performance is negatively correlated with repetition spacings; when the retention interval is long relative to the spacing intervals, performance is positively correlated with the spacing of repetitions." (p. 528). The earliest study that demonstrated this was Peterson *et al.* (1962), where word–number pairs were studied either massed or spaced (8 s apart) and then tested either 2, 4, 8, or 16 s later. Results showed that massed study led to better recall at the 2- and 4-s test intervals, while spaced study led to better recall at the 8- and 16-s intervals. In the motor domain too, blocked practice would probably be the smart way to prepare for an imminent test, or as a warm-up strategy. Cepeda *et al.*'s (2008, p. 1100, Fig. 4) temporal ridgeline illustration, replicated here in Fig. 2, provides further evidence in their three-dimensional surface, where recall is shown to be dependent on the interaction between spacing of repeated items during study and the ensuing delay until testing occurs. At zero test delay, recall is an inverse linear function of study gap, but as test delay increases, optimal recall is found to be a changing non-monotonic function of study gap.

However, recently, a meta-analysis (Cepeda *et al.* 2006) found that even when the test occurred after *less than* 1 min had elapsed, spacing was slightly better than massing. Of course, as the retention interval increased, the spacing effect also strengthened. Furthermore, the authors point out that a massing effect had only occurred for retention intervals that were remarkably short—less than a few seconds—which would be unlikely to occur in a classroom context. Quizzes, tests, and exams typically take place once a longer period of time (certainly more than a few seconds) after study has elapsed, and thus, spaced study, as a rule of thumb, would be the more effective strategy.

On the flipside, one of the most crucial differences between laboratory learning and classroom learning is the length of time between study and test. Learning in the real world can take days, weeks, months, and even years, as compared to the vast majority of cognitive spacing research, which could take place across only minutes or even seconds. However,

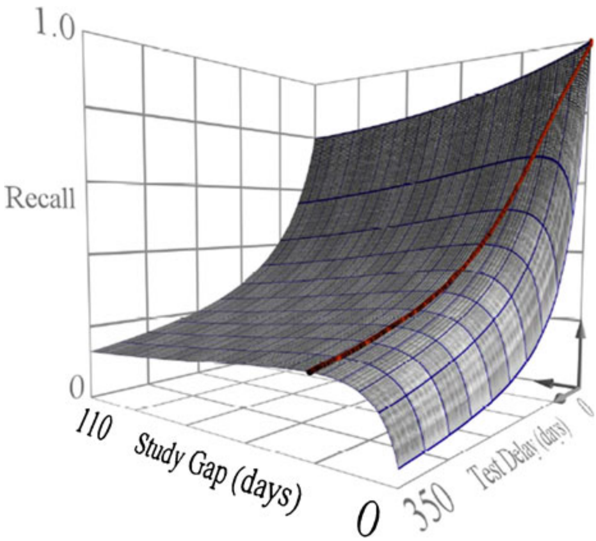

Fig. 2 A functional approximation of recall on the final test (as a proportion), plotted as a function of gap and test delay (i.e., retention interval). The location of the ridgeline indicates that, as test delay increases, optimal gap increases while there is a decrease in the ratio of optimal gap to test delay (taken from Cepeda *et al.* 2008, Fig. 4)

even across very long delays, the spacing effect has been supported for materials that have included real-world-type materials, such as maps (e.g., Carpenter and Pashler 2007), foreign languages (e.g., Bahrick *et al.* 1993), history facts (e.g., Carpenter *et al.* 2009), typing (Baddeley and Longman 1978), and math learning (e.g., Rohrer and Taylor 2006). Some data have also shown that an additional massed session is no better than a single reading of a text (spacing has significant benefits, see Rawson and Kintsch 2005). As a result, there have already been pushes for spaced learning and teaching in the schools (Pashler *et al.* 2007; Roediger *et al.* 2010).

As an interim conclusion, the historically consistent spacing effect has received positive reviews from both the cognitive and motor literature, as well as from data collected from younger populations and when using realistic contexts and materials, particularly when keeping in mind ecological validity. The key subsequent question then is do people use spacing strategies? From here on, we discuss some of the issues regarding spontaneous strategies regarding distribution of study and, in particular, whether individual learners know to use spacing rather than massing practices.

Metacognition and the Spacing Effect

Metacognition, or the process of using one's own judgments to guide study choices, is crucial for learning. If a student studies ineffectively or randomly, then it is likely that test performance will be poor. A recent interest in the distribution of study has included the individual's metacognitive control of spacing versus massing. Specifically, do people use the more beneficial spaced strategy, and not the massing strategy, when studying? If they do, educators should be happy that the effective strategy seems to be a spontaneous one. If they do not, then we may suggest and test ways in which to increase the probability of spacing study.

There have in fact been a handful of studies that have looked at the impressions people have of spacing, and whether people choose to space their learning in the real world. In general, people, including adults, predominantly prefer massed practice (for a recent example, see Kornell and Bjork 2008). In the above-described Baddeley and Longman's (1978) study, for example, after postal workers practiced typing in either massed or spaced study sessions, they had to indicate how satisfied they were with the training. Results showed that while spacing led to the best learning, it was the *least* liked. Similarly, Simon and Bjork (2001) found that people preferred the massing strategy on a motor learning task. In learning a set of multi-segment movement tasks, learners under blocked practice conditions predicted superior retention performance as compared to those under random practice conditions. In fact, and as described above for the basic contextual interference effect, the opposite results emerged. It seems that learners are far more sensitive to their immediate performance levels than to the actual learning benefits that are accruing as a result of practice, making them relatively poorly equipped to judge how well they are learning during learning.

When learners do not choose an effective (i.e., spacing) strategy should we intervene and encourage spaced study schedules? Inherent in this question is the question of whether we believe that the learner himself/herself should not be his/her own decision maker. The notion that people may not use the best strategies is not new. When investigating the time-allocation decisions that people made as compared to a computer-controlled allocation of study, Atkinson (1972) concluded: “My data, and the data of others, indicate that the learner is not a particularly effective decision maker.” (p. 388). More recent data have shown that people believe that re-reading is a more favorable strategy than generating or self-testing—the opposite is true (Karpicke *et al.* 2009; Kornell and Son 2009; Son and Kornell 2010). When it comes to massing versus spacing, again, students believe, incorrectly, that massing leads to better performance than spacing (Kornell and Bjork 2008; McCabe 2011; Metcalfe *et al.* 2007).

Up until quite recently, surprisingly, among the studies that have tested the effects of massing versus spacing, virtually none has investigated self-selected or metacognitive spacing strategies. In 2004, the first study on metacognitively controlled spacing was developed and tested. In that study, college students were presented with cue-target pairs and could control the amount of time that elapsed before re-studying each of the pairs (Son 2004). For each original pair presentation, they were first asked to make a judgment about how well they would remember the pair, and then, whether they wanted to *mass*—by pressing a “study now” button—or to *space*—by pressing a “study later” button—their study of that pair. If they chose to *mass*, then the same pair was presented again immediately; if they chose to *space*, then that pair was presented after a delay. They also had the option of clicking a “Done” button for any of the pairs, if they felt that no further study was necessary. If this button were pressed, that pair would be dropped from the re-study list. The results showed that college students, propitiously, tended to *space* their study—doing so more than 50 % of the time—and systematically, the distribution was dependent on one's metacognitive judgments. Specifically, people chose to distribute the items they thought would be easier to learn and mass the judged-difficult items (also see Pyc and Dunlosky 2010, for a replication; but see Benjamin and Bird 2006; Toppino and Cohen 2010, for discordant results using different methods, and Toppino *et al.* 2009a, for a potential rectification, where massing might occur when an item is not yet fully encoded). Furthermore, in a later study, when the college students' choices to space were *honored*, that is, when they were allowed to re-study in the manner that they chose for each pair, they performed better than when their choices were *dishonored*, suggesting that their spacing choices were effective and likely directed at enhancing learning (Son 2010).

The data from this particular population of college-aged individuals indicate a good strategy for the distribution of study: When studying vocabulary word pairs, individuals do select to space their study, and tend to mass only when the learning is relatively difficult. These results also support the notion that while spacing is effective, expanding study may sometimes be better than uniform spacing (Landauer and Bjork 1978). In theory, the benefits of spacing can pan out only when the item, at first study, has been encoded to the degree that it will not be completely forgotten before additional study has taken place. In other words, when an item's learned state is tenuous—or when metacognitive judgments are low—it appears that a massing strategy would be more beneficial. The data also support the more recent findings of Pavlik and Anderson's (2003) ACT-R model of the relationship between spacing and decay. They stated: "Our mechanism is…quite plausible in light of theories of spacing and memory that propose that the benefit of additional practice is mediated by the difficulty of that additional practice." (p. 181).

Data from a similar experiment, on the other hand, showed that, in contrast to the college students, young children—in the first grade—did not choose effectively. They tended to mass their study, and did so regardless of how easy or difficult they judged the item to be (Son 2005). In a recent experiment testing third and fifth graders, performance after honoring and dishonoring their choices was also compared, as had been done with the college students. The results were, again, very different from those of the college students, and more similar to the first grade children—they chose to mass their study over 65 % of time, regardless of whether they judged the item to be easy or difficult to learn. Moreover, dishonoring their massing choices and imposing a spacing strategy greatly improved final test performance (Son 2010).

Thus, while the college-aged students seemed to be distributing their study and doing so effectively, the elementary school-aged children did not. On the positive side, at least for children, we can gain benefits by encouraging strategies independent of the metacognitive states that produce the choices. However, the fact that the adults' performance did not improve supports the notion that metacognitive decisions cannot be completely discounted.

Why might children choose to mass rather than to space their study? An obvious explanation, one that results from the theories described above, is that massing takes less effort than spacing. That is, spacing may be *undesirably* difficult. Indeed, studies have shown that during spaced study, acquisition is not only slower but also confidence in one's learning is lower as well (Bahrick *et al.* 1993; Zechmeister and Shaughnessy 1980). Another explanation might be that spaced study, ironically, entails that the learner stop studying now, but will have to come back to it at some later time. In this sense, spaced study might be thought of as studying again, whereas massed study might give the illusion of less study time (even though, of course, the total study times in the two conditions are equivalent). This would especially be a problem if children were not motivated to re-study in the first place.

Indeed, the Son (2004) study showed that the college-aged participants almost exclusively selected the "Done" button only for the very highest JOL items. Figure 3 illustrates the proportion of choices of massed, spaced, or done as a function of people's metacognitive judgments (taken from Son 2004, Fig. 1). As can be seen, the college students were motivated in that they did choose, for the majority of items, to re-study.[1] When this paradigm

[1] The figure also shows the probability correct on the test conditional on each choice. This probability correct is the number given above each bar. Adults chose to re-study—either massed or spaced—those items in which they were not completely confident. Note, also, that the items given the highest judgments that participants chose not to re-study were poorly remembered (0.14 correct). Thus, there is room for improvement even in adults. Even though they declined to study only on very high judgments, nevertheless, they, too, appeared to have opted out of study prematurely.

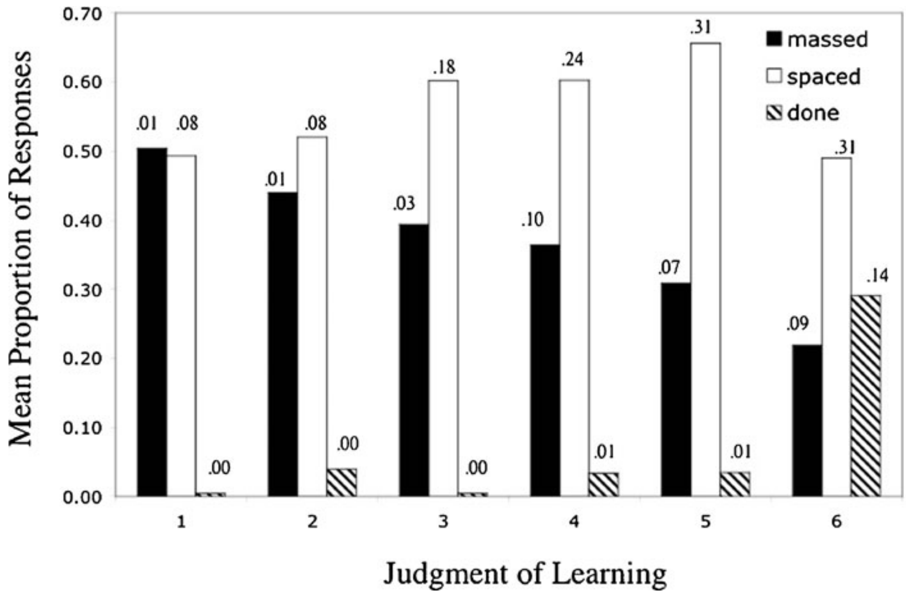

Fig. 3 The mean proportion of massed, spaced, and "done" choices as a function of metacognitive judgments of learning (JOL) level. Higher levels represent items that are judged as easier. The *numerical values above each bar* indicate the proportion correct at final (long-term) test (taken from Son 2004, Fig. 1)

was tested in children, a problem was encountered—the first few children who were tested chose the "Done" button virtually all the time (see Son 2005). As a result, whether they would choose to mass or to space could not be determined. The decision was made at the time to remove the Done button and force the children to choose mass or a space practice. It was then that the first graders preferred massed study, regardless of their judgments, and as described above, as well as did the third and fifth graders, revealing a less than optimal strategy. However, the likelihood remains that if the children had had the done option, their choices would have been even more suboptimal. Thus, a complicated problem with the spacing versus massing paradigm is that there is no way of knowing whether the two strategies—massing and spacing—feel equal to the learner in terms of efficiency or perceived effort.

A final explanation we touch upon here for why children might prefer the less optimal massing strategy may be because spacing requires experience. In particular, spacing one's study requires that a long-term time frame is understood. In the discussion of Son (2005), this hypothesis—that young children do not understand what it means to study in the long-term future—was proposed as a way of explaining the dysfunctional strategies of the first graders. In that same study, in fact, there was evidence showing that the same first grade children did use their metacognitive judgments to guide behavior systematically, *when both of the study choices panned out in the short term*. When presented with word pairs, the first graders were systematic when they were asked whether they would like to "read" the pair again or whether they wanted to "test" themselves. Results showed that first graders tended to read the items that were judged as difficult but tested themselves when the items were judged as easier. These data suggest that even children as young as grade 1 do use their metacognitive judgments spontaneously to guide their study behavior—in this case, reaping the benefits of self-testing—but a spacing strategy may be qualitatively more complicated given that its occurrence is at some later, unspecified time.

In short, the spacing strategy seems, unfortunately, to be the more unattractive strategy in a number of ways. It is more difficult during study; it can be perceived as an additional study trial (whereas massing is by definition only one trial, albeit a long one), and some populations, such as young children, may have difficulty understanding what it means to come back to studying at a time in the long-term future. Fortunately, for college-aged students, the spacing strategy seems to be preferred, and spacing effects are obtained. However, a caveat is that not nearly enough research has been conducted regarding these metacognitively selected strategies. It may be that some other adult populations do not necessarily choose the more effective strategy. Even the same college students may have very different study choices if the materials or the methods were to be different. What we do know for sure is that there is a difference in distribution of study choices by age—younger students prefer to mass their learning. The silver lining, though, is that performance can be boosted by encouraging spacing practices.

Implications for Education

On the whole, both in the laboratory and the classroom, both in adults and children, and in the cognitive and motor learning domains, spacing leads to better performance than massing. In addition, while there are very particular situations for when the results flip—as in extremely short retention delays or when to-be-learned items have not yet been appropriately encoded—these environments are relatively rare in the real world, as learning occurs across relatively long ranges of time. Thus, the past and ongoing data provide consistent implications for education, both for the educator and the individual learner: Spacing study is the optimal strategy.

Still, much remains to be investigated. Researchers should continue to conduct more tests on spacing versus massing, and branch out into using a variety of materials, with the larger goal of confirming (or disconfirming) the universality of the spacing effect. We do know that there may be cases where spacing is not the best strategy—such as in the expanding retrieval paradigm, where spacing too far apart may be hurtful (which is, anyway, rather unrealistic given that feedback is usually provided in the real world)—but knowing the exact dimensions across various domains of school topics (e.g., mathematics, problem solving, and reading comprehension) is crucial if the field is to move forward.

Inside the classroom, the first obvious step for researchers is to continue to make a conscientious effort to connect with practitioners regarding the spacing literature. The bridge between researchers and educators on this topic have begun to be firmly established—many practitioners are now aware of the benefits of spacing—and both sides should continue to consider the complexities of learning, while thinking of creative new ways to incorporate spacing strategies. For instance, educators might consider the possibility of implementing more review sessions, and perhaps even more quizzes, that are evaluated *but not necessarily graded*. Students, even very young children, seem to enjoy testing themselves (as was shown in Son 2005), particularly when they are confident in their answers. By using the ungraded quizzing method, educators can encourage effective strategies of both spacing and self-testing while discouraging the stress that is so often connected with test-taking in school.

Another potential way in which to incorporate the benefits of spacing into the classroom is to increase *contextual variability* (e.g., Raaijmakers 2003). Spacing in and of itself seems to work because of increased contextualization, and one could think of methods to take advantage of this mechanism. For instance, co-teaching within a given topic would increase the variability of how that topic is perceived (and co-teaching by definition is likely to be accompanied by a spaced learning session). Allowing different contexts in which to have individuals learn a topic would also be helpful. For example, something as basic as learning vocabulary word definitions could be learned using a host of context sentences, rather than merely one or two. Even allowing students to report how they would approach a particular science problem or reading comprehension task would also increase the contextual variability of the classroom learning environment, allowing for a greater number of retrieval cues in the long term.

Realistically, though, because of the vast amount of information that needs to be covered, and the lack of time, it is reasonable to assume that spacing strategies may not be consistently incorporated into the classroom. Most will say that there is little time for ungraded quizzes, co-teaching, and discussions between students during class time. Indeed, many classroom topics are presented only once, and unfortunately, the same is often the case for textbooks, from which students do their homework (Saxon 1982; Stigler *et al.* 1982). Thus, a more effective strategy, when thinking about implementing spacing strategies, might be to focus on how the individual can think about ways in which to space their study, as we discuss below.

Children, spanning the entire range of elementary school and continuing into adulthood, experience the bulk of learning when they are on their own. Many children, unfortunately, are not benefiting from the practice of homework (Cooper *et al.* 2006). A key aspect of learning is that there should be practical ways of incorporating effective strategies such as spacing into learning sessions outside the classroom. A way in which spacing has already been used in homework is in the mixing and spacing of math problems (e.g., Taylor and Rohrer 2010). Similarly, children should receive homework assignments, in every domain, that cover mixed topics, and not only the one topic that was covered in the class on that day. That is, students should be encouraged to study materials that cover, for instance, a new topic *and* an old review topic. While the assignment may feel more difficult to the student (given that they may not remember the older lesson), the benefits of spacing are sure to show up in the long run, especially for a final test, where many of the questions refer to content from long ago.

Another recommendation for practitioners regarding individual learning is to have students take explicit metacognitive control of their strategies and to state why they choose particular strategies. It is, in fact, as of yet unknown whether young children are even aware of choosing to mass rather than space. In the honor/dishonor experiment (Son 2010), anecdotal results suggest that many of the young children did not even realize when a particular choice was being dishonored—they never seemed shocked or frustrated—suggesting a lack of explicit control. There are ways in which to foster self-regulation, including simply asking students to write down the strategies they use when studying on their own. These strategies would be open ended—and could include those such as reading, re-reading, self-testing, and even spacing versus massing. Indeed, many have discussed the importance of having personal goals and carrying them out appropriately for successful learning (e.g., Hattie *et al.* 1996; Zimmerman 2000). Some also emphasize the importance of teaching explicit self-regulatory strategies to children at very young ages (e.g., Brown *et al.* 2005; Hendy and Whitebread 2000; Stoeger and Ziegler 2005). If students are required, in some way, to explicitly express their strategies, two things could occur: First, students would become more aware of the strategies and possibly understand sooner whether they are effective or ineffective. Second, teachers and researchers would have a better understanding of how self-regulatory strategies develop. The challenge for teachers, though, is to find the balance between teaching subject content and teaching metacognitive strategies.

For distribution of study strategies in particular, one way to encourage spacing during homework is to use summarization, at some delay. For example, having students write short summaries of a past lesson would be beneficial, as it would require them to experience the effort and “desirable” difficulty of reviewing older materials. This strategy could be used in the classroom as well as outside the classroom as a homework assignment. The assignment would be effective in that it would emphasize a learner's *individual* strategy. In other words, as was shown by Son (2004)'s massing and spacing strategies as guided by judgments, as well as the expanding practice results, learners are likely to have heterogeneous “optimal” spacing delays depending on whether the items are judged as relatively easy or difficult. After all, within a classroom, ranges of ability may be quite large. Thus, the summarization schedule for each student can differ, depending on level of ability: For the poorest learners, an almost massed summarization session might help, especially if the content is not sufficiently encoded. On the other hand, for the strongest students, a longer delay can ensue before having to write a summary.

Finally, students should be made aware of potential metacognitive misconceptions that can occur. Research has shown that people believe that massed practice is better than spaced practice (e.g., Zechmeister and Shaughnessy 1980), perhaps due to the fact that massing is faster and less effortful in the short term. For very young learners, it may not be feasible to teach the differences between knowing now and retaining in the long term. However, certainly in later elementary school, students have the ability to understand the illusion. A challenge for practitioners is to find ways in which to make difficulty and effort desirable, or at least not completely aversive, as so many students will feel. A few ways to increase a child's motivation could be to use computers for learning (e.g., Metcalfe *et al.* 2007), or to frame the learning as a game, where learners can earn points for effective learning (e.g., Dunlosky and Thiede 1998).

Conclusion

In this review paper, we have presented data and theory related to the spacing effect, and have focused on the importance of spaced strategies within educational contexts, where long-term performance is crucial for academic success. We have discussed the challenges that exist for the practitioner and the learner, including the lack of awareness of the benefits of spacing, and the *undesirable* difficulties of spacing in the here and now. These challenges exist especially for young children, who, nevertheless, are required to spend significant amounts of time studying on their own outside the classroom, and unfortunately, may be studying in ineffective and inefficient ways.

On the bright side, the field is much closer to understanding the different ways of scheduling study, and the benefits that result, both in using controlled laboratory stimuli as well as when using real-world learning stimuli. We now know, for instance, that enforcing spacing strategies can boost learning to a considerable degree in the laboratory, particularly in children (e.g., Son 2005), which gives learners and educators a benchmark in the classroom. The next step is to think of ways in which to allow children to understand *why* spacing is helpful, while emphasizing the importance of long-term retention and transfer.

In conclusion, we have proposed a short list of recommendations for practitioners as to how spacing strategies may be achieved during learning, both inside and outside the classroom. Even just a few years back, the two fields—psychology and education—could be described as almost mutually exclusive. Indeed, many teachers had not been aware of the benefits of spacing one's learning (Son 2007), and it was uncommon for researchers to set foot outside of their laboratory. Making steps to bridge this gap has allowed psychologists to design more practical studies, which, in turn, has begun to allow for more pragmatic applications during real-world instruction.

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